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MICROWAVE TRANSVERSAL EQUALIZER OPEN LOOP ADAPTIVE COMPUTER CONTROL TECHNIQUES

Eaton Corporation

A. Leber
G. Kanischak
D. Wang
M. Daigle
R. Indin

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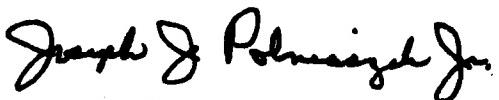
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APPROVED:



JOSEPH J. POLNIAZEK, JR.
Project Engineer

APPROVED:



FRANK J. REHM
Technical Director
Surveillance Division

FOR THE COMMANDER:



JOHN P. HUSS
Acting Chief, Plans Office

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SUMMARY

This final report on Contract F30602-80-C-0042 summarizes the AIL investigation to determine and demonstrate suitable algorithms and corresponding computer software in order to provide open-loop adaptive control of the Microwave Transversal Equalizer (MTE) previously developed by AIL under Contract F3062-78-C-0352.

The program task objectives have been successfully accomplished by AIL with the application of Fast Fourier Transform (FFT) techniques to provide an algorithm programmed on the RADC HP 2100A computer. This procedure will ultimately be utilized to determine the MTE amplitude and time delay adjustments necessary to equalize the distortion introduced by an arbitrary network in series with the equalizer.

Verification of the developed FFT and associated software program was accomplished at AIL with a DEC-20 computer using artificially generated simulated time sidelobe distortion typical of the expected range of levels. Translation of the algorithm from the DEC-20 computer format to the HP 2100A computer format has been completed, and verification of the software program using RADC I and Q data is underway. Preliminary data suggests that the program translation task has been successfully accomplished by AIL. It is expected that optimal data acquisition techniques and/or preferred computer interface procedures will be defined as a result of related post-delivery activities at RADC.

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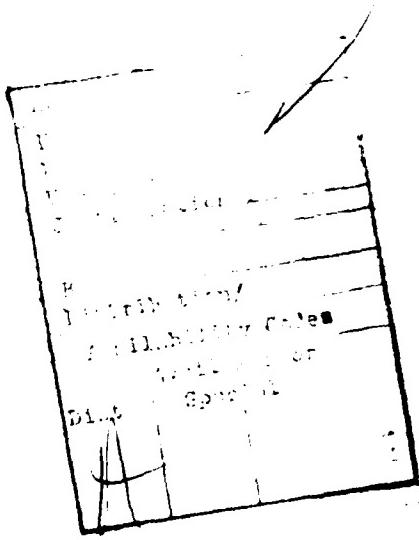


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1. INTRODUCTION

The objective of Contract F30602-80-C-0042 is to develop an algorithm, and relevant computer software programming for the RADC HP 2100A computer, to facilitate open-loop control of the MTE in order to minimize time sidelobe distortion. The resultant algorithm using FFT techniques and associated programming has been validated with artificially generated simulated distortion data using the AIL DEC-20 computer and the HP 2100A computer at RADC. A similar post-delivery validation effort will be conducted by RADC personnel using real-time distortion data and the HP 2100A computer.

Section 2.0 will contain a brief discussion of MTE operational fundamentals in order to establish an inter-relationship with the algorithm development program. Section 3.0 will present a detailed treatment of the FFT techniques applied to algorithm development for the MTE. Section 4.0 will discuss the resultant computer program including applicable operating and test procedures. Finally, Section 5.0 will present conclusions and recommendations for a logical continuation of effort required to provide closed-loop operation of the MTE.

2. MTE TECHNICAL DISCUSSION

A discussion of distortion considerations and the fundamentals of the MTE operation are presented in order to provide the technical basis for computer control and adaptive equalization of resultant time sidelobe distortion. A detailed description of the MTE, including operating procedures, is included in Final Report RADC-TR-80-121 of 31 January 1980 titled "Microwave Transversal Equalizer".

2.1 PAIRED ECHO THEORY AND DISTORTION CONSIDERATIONS

Algorithms for determining the settings of attenuation and phase for each loop of a transversal equalizer rely heavily on the paired echo concept. Accordingly, a brief review of this theory is given below stressing its applicability to the present program.

2.1.1 Paired Echo Theory

The paired echo concept and its application to the design of a transveral equalizer (MTE) was described in Ref. 1. It should be noted that this work was supported by RADC. This paper also gives a bibliography of prior work on non-microwave MTE's and the now classic reference on Chirp radar by Klander, et al. The latter emphasized the use of paired echo theory to predict time sidelobe levels in Chirp radars. The essential aspects of the paired echo theory are summarized below.

Ref. 1 - J.J. Taub and G.P. Kurpis, "Microwave Transversal Equalizer", *Microwave Journal*, 1969.

Signals which can be characterized by a time function of its Fourier transform (amplitude and phase vs frequency functions), are subject to distortion when propagating through a microwave component or a system of microwave components (such as a Chirp radar). This distortion occurs because the system's transfer function possesses neither perfectly constant gain nor perfectly linear phase over the spectrum of the signal.

We typically represent the transfer function in the frequency domain and need to predict its effect on time domain distortion. By using the paired theory we can make relatively quick conversions between the frequency domain and the time domain and vice versa.

The system transfer function, or frequency response, of an arbitrary system can be defined as:

$$H(\omega) = A(\omega) e^{jB(\omega)} \quad (2-1)$$

where A and B are respective gain and phase functions defined in Reference 1.

We must now assume that the signal transmitted through the system has spectral components that are band limited. This is a safe assumption for most systems. For example, in many radar applications the signal's spectrum is confined to the electronic bandwidth of the final power amplifier. Within a band limit of ω_L to ω_H we can rigorously represent the A and B functions as Fourier series:

$$A(\omega) = a_0 \left[1 + \sum_{n=1}^N \frac{a_n}{a_0} \cos(n\omega'e) + \phi_n \right] \quad (2-2)$$

and

$$B(\omega) = b_0 \omega' + \sum_{n=1}^N b_n \sin(n\omega'e + \psi_n) + K \quad (2-3)$$

where:

$$\omega' = \omega - \omega_0$$

$$\omega_0 = \frac{\omega_l + \omega_h}{2}$$

$$e = \frac{2\pi}{\omega_0 - \omega_l}$$

In a distortionless network $A(\omega) = a_0$ and $B(\omega) = b_0 \omega'$

Hence the remaining terms contribute to distortion. This representation leads to the time domain response including distortion and so that for a band limited signal $v_i(\omega)$ and its time function equivalent $v_i(t)$ we obtain

$$v_o(t) = a_0 v_i(T + b_0) + a_0 \sum_{n=1}^N E_{n+} v_i(t+b_0 - ne) \\ + a_0 \sum_{n=1}^N E_{n-} v_i(t+b_0 + ne) \quad (2-4)$$

where $v_o(t)$ is the output time function and the constants E_{n+} and E_{n-} represent echo or time sidelobe amplitude levels. These levels are related to the Fourier distortion coefficients in equations (2-2) and (2-3). For the case where ϕ_0 and $\psi_0 = 0$ they reduce to

$$E_{n+} = \frac{1}{2} \left(\frac{a_n}{a_0} + b_n \right) \quad (2-5)$$

$$E_{n-} = \frac{1}{2} \left(\frac{a_n}{a_0} - b_n \right)$$

A typical example of a distorted microwave pulse is given in Figure 2-1. The echoes are clearly displayed. This analysis demonstrates that a frequency domain transfer function can be represented by a Fourier series which enables rapid calculation of the time domain response. Conversely, a measurement of the time domain response which yields sidelobe levels can be used to rapidly calculate the a and b coefficients thereby yielding the frequency domain transfer function. The MTE settings cancel distortion by injecting equal and opposite echoes in cascade with the system.

2.1.2 Use of Paired Echo Theory

Since the MTE design and adjustment procedures are based on cancelling distortion echoes, algorithms can be developed by taking either frequency domain (I and Q data) measurements or time domain responses (time sidelobe levels in dB) and converting them into the necessary MTE loop attenuation and phase settings to produce cancelling echoes. The key point of this discussion is that use of paired echo theory simplifies computation and therefore significantly reduces computer time. Furthermore it provides the flexibility to work with either frequency or time domain data. In this program the actual procedure used was to use I and Q data (frequency domain measurements).

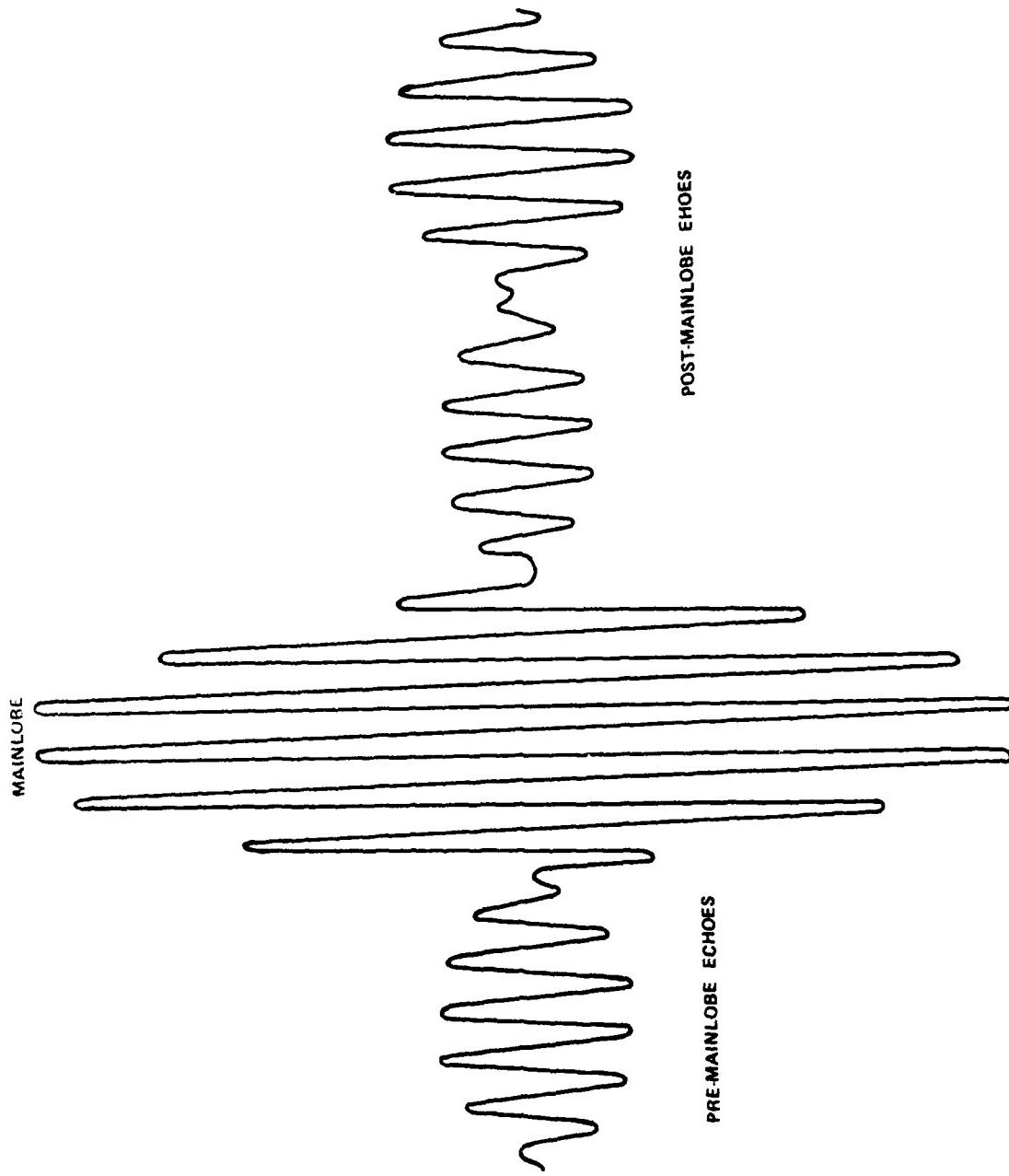


Figure 2-1. Time Sidelobe Distortion.

2.2 MICROWAVE TRANSVERAL EQUALIZER OPERATION

The MTE has been designed by AIL to cancel the parasitic time sidelobes caused by distortion, by generating its own artificial equalizer sidelobes, whose envelopes are properly delayed (or advanced) to coincide in time with the parasitic sidelobes. In addition, the amplitude and phase of each artificial sidelobe can be separately adjusted to produce an equal amplitude phase reversed replica of the corresponding parasitic sidelobe.

Generation of the equalizer echoes is accomplished by tapping off portions of energy from the main signal lobe on the main transmission path, directing these portions through properly adjusted delay lines and reintroducing the delayed signal portions back into the main transmission path with proper amplitudes and polarity. The time domain output response of an ideal MTE is shown in Figure 2-2. It should be noted however that the actual response will consist of a train of echoes with decreasing amplitudes (0.75 dB/tap) due to the insertion loss of the mainline tapped delay elements. A correction for the aforementioned MTE echo transfer characteristics will be necessary in order to achieve the desired tap attenuator setting with adaptive closed loop operation (computer controlled).

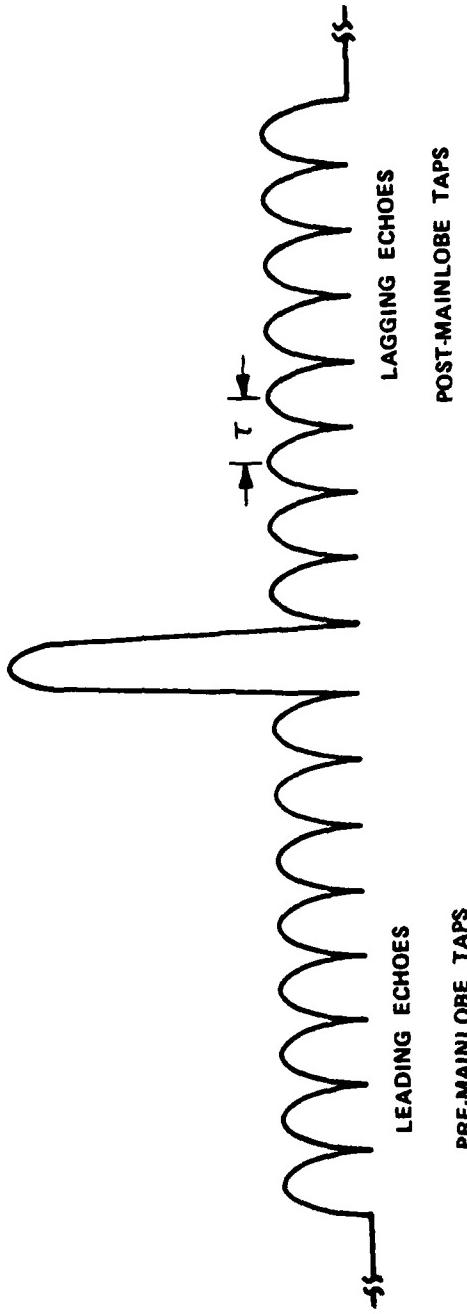


Figure 2-2. Time Domain Output of Microwave Transversal Equalizer.

The MTE consists of four cascade connected microwave integrated circuit mainlines and 32 secondary lines for the purpose of generating a train of 8 pre- and post-mainlobe echoes (16 total). A 3.3 nsec time delay between echoes of each train is provided.* The amplitude level and time delay of the selected 16 of the 32 possible echoes are individually adjusted with the PIN diode variable attenuator (electronically controlled), a line stretcher variable delay (mechanically controlled), included in each secondary line. The remaining 16 echo taps are terminated, however these taps are available for use as required.

It should be noted that the transfer characteristics of each of the 16 variable attenuators, as well as the 16 variable solid state time delay units (when they are developed) are required to properly achieve adaptive MTE control.

*Compatible with a 300 MHz bandwidth.

3. ALGORITHM DEVELOPMENT

An algorithm has been developed using FFT techniques to provide open loop control of the MTE. The technique will be described in terms of the relevant input and output formats, as well as the FFT algorithm.

3.1 INPUT FORMAT

The input to the FFT consists of a set of complex correlations as a function of frequency. These samples can be expressed by

$$H(j\omega_i) \approx I(\omega_i) + jQ(\omega_i) \quad (3-1)$$

where

ω_i is the i^{th} frequency

$I(\omega_i)$ is the in-phase frequency response

$Q(\omega_i)$ is the quad-phase frequency response

For the problem at hand, the following frequencies are considered:

$$\omega_i = 2\pi [f_L + (i-1) \Delta f], \quad i = 1, 2, \dots, 256 \quad (3-2)$$

where

$$f_L = 3.1 \text{ GHz}$$

$$\Delta f = 1.17647 \text{ MHz} \approx 1.18 \text{ MHz}$$

The last frequency is found by setting $i = 256$; that is,

$$f_H = 3.1 + 255 \times 1.18 \times 10^{-3} \approx 3.4 \text{ GHz}$$

As a result, a total of 255 pairs of measurement data are involved for a bandwidth of 300 MHz as shown in the format presented in Table 3-1.

TABLE 3-1. TAPE FORMAT FOR THE FREQUENCY RESPONSE

| Word Index | Notation | Frequency |
|------------|--------------------|----------------------|
| 1 | $I(j\omega_1)$ | 3.1 GHz |
| 2 | $Q(j\omega_1)$ | 3.1 GHz |
| 3 | $I(j\omega_2)$ | 3.1 + Δf |
| 4 | $Q(j\omega_2)$ | 3.1 + Δf |
| 0 | 0 | 0 |
| 0 | 0 | 0 |
| 0 | 0 | 0 |
| 509 | $I(j\omega_{255})$ | 3.1 + 254 Δf |
| 510 | $Q(j\omega_{255})$ | 3.1 + 254 Δf |
| 511 | $I(j\omega_{256})$ | 3.4 GHz |
| 512 | $Q(j\omega_{256})$ | 3.4 GHz |

Note:

1. $\Delta f = \frac{3.4 - 3.1}{255 \times 10^{-3}} \approx 1.18 \text{ MHz}$

2. Each word is represented by 8 bits in binary 2's complement notation; i.e.:

$$-128 < I, Q < +127$$

The above representation defines the formula transformation required from the input medium to the computer.

The input samples are represented by an 8 bit binary two's complement notation. Thus, a word is defined to be 8 bit with the value of the word ranged from 127 to -128. In floating point notation the value is ranged from

$$127/128 = 0.992188 \text{ to}$$
$$-128/128 = -1$$

3.2 OUTPUT FORMAT

The output of the FFT consists of a set of $N_t = 17$ complex MTE tap coefficients which represents a truncated Fourier series representation of the equalizer transfer function. The total number of relative equalizer taps is sixteen with the center tap (number 9) taken as the reference tap.

The output tap coefficient will be presented by decimal representation with the absolute magnitude of the tap less than unity, that is: $-1 \leq C_i < 1$ for $i = 1, 2, \dots, 17$ and phase angle is expressed in degree units.

Further data format transformation will be needed to match the exact setting on the MTE attenuator dial.

3.3 FFT ALGORITHM

Consider again the measured frequency response of a network with a transfer function $H(j\omega_i)$. The measurement can be functionally described by the block diagram shown in Figure 3-1. The input signal to the device can be written as

$$x_i(t) = A_i \cos(\omega_i t + \theta_0) \quad (3-3)$$

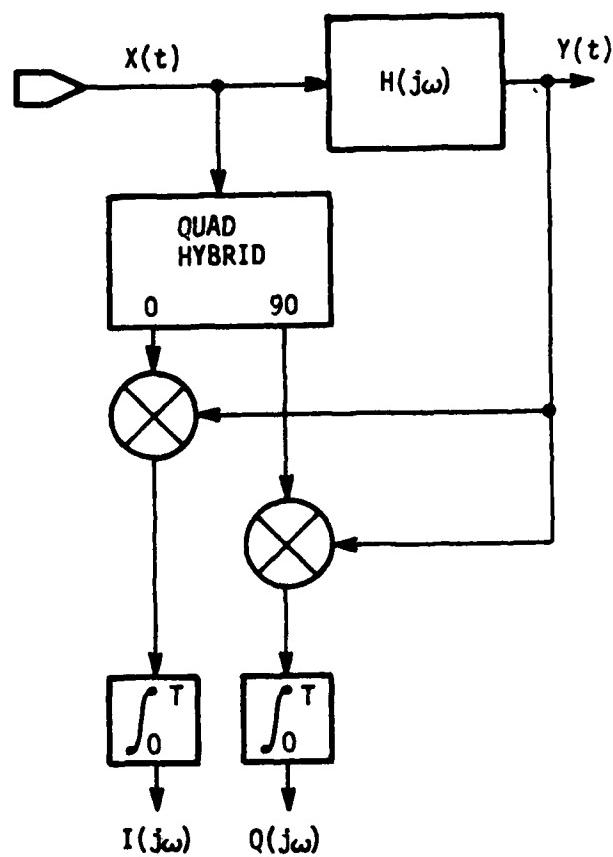


FIGURE 3-1. MEASUREMENT SETUP

where

ω_i is the i^{th} in-band frequency

θ_0 is the input phase angle

A is the amplitude of the signal

The response of the network is

$$Y_i(t) = B_i \cos(\omega_i t + \theta_i) \quad (3-4)$$

where

θ_i is the corresponding phase angle for the i^{th} signal

B_i is the corresponding amplitude for the i^{th} signal

The quadrature hybrid is used to generate the in-phase and the quad-phase components:

$$I(j\omega_i) = \frac{1}{T} \int_0^T A \cdot B_i \cos(\omega_i t + \theta_0) \cos(\omega_i t + \theta_i) dt \quad (3-5)$$

and

$$Q(j\omega_i) = \frac{1}{T} \int_0^T A \cdot B_i \sin(\omega_i t + \theta_0) \cos(\omega_i t + \theta_i) dt \quad (3-6)$$

where T is defined as the correlation time. The correlator output can be reduced to

$$I(j\omega_i) = \frac{AB_i}{2} \cos(\theta_0 - \theta_i) \quad (3-7)$$

$$Q(j\omega_i) = \frac{AB_i}{2} \sin(\theta_0 - \theta_i) \quad (3-8)$$

The gain and phase response as a function of frequency can be expressed by

$$G_i = \sqrt{I_i^2 + Q_i^2} = \frac{A}{2} \cdot B_i \quad (3-9)$$

$$\theta_i = \tan^{-1}\left(\frac{Q_i}{I_i}\right) + \theta_0 \quad (3-10)$$

where the short hand notation is adapted; that is

$$I_i = I(j\omega_i) \text{ and } Q_i = Q(j\omega_i)$$

Since A and θ_0 are not a function of frequency, these measurement data represent the transfer function $H(j\omega_i)$. The impulse response $h(nT)$ can be found by discrete Fourier transform method.

A few assumptions will be made such that the Fourier series approach can be applied:

(1) Signals passing through the network will be bandlimited to 300 MHz. To provide equalization over this bandwidth requires a corresponding time delay. This defines the delay between taps to be:

$$T = \frac{1}{f_H - f_L} = \frac{1}{300 \times 10^6} = 3.33 \text{ nsec}$$

(2) Since any digital filter spectrum to be realized will be made periodic of period f_s , then the spectrum can be represented by a Fourier series:

$$H(j\omega) = \sum_{k=-\infty}^{\infty} c_k \exp(jk\omega T) \quad (3-11)$$

where c_k is the k^{th} Fourier coefficient defined by

$$c_k = \frac{1}{\omega_s} \int_{-\frac{\omega_s}{2}}^{\frac{\omega_s}{2}} H(j\omega) \exp(-jk\omega T) d\omega \quad (3-12)$$

Generally, if the gain response is an even function and the phase response is an odd function, that is

$$G(j\omega) = G(-j\omega) \quad (3-13)$$

$$\theta(j\omega) = -\theta(-j\omega) \quad (3-14)$$

then the resultant coefficients will be real. Note that these requirements that $G(j\omega)$ and $\theta(j\omega)$ be even and odd respectively, lead to similar requirements that the in-phase and the quadrature-phase components to be even and odd, respectively. In practice, however, these symmetries cannot be assumed as shown in Figure 3-2. As a result, the coefficients will be complex; that is:

$$c_k = a_k + j b_k, \quad k = 1, 2, \dots, 17 \quad (3-15)$$

where

$$g_k = \sqrt{a_k^2 + b_k^2} \quad (3-16)$$

$$\theta_k = \tan^{-1} (b_k/a_k) \quad (3-17)$$

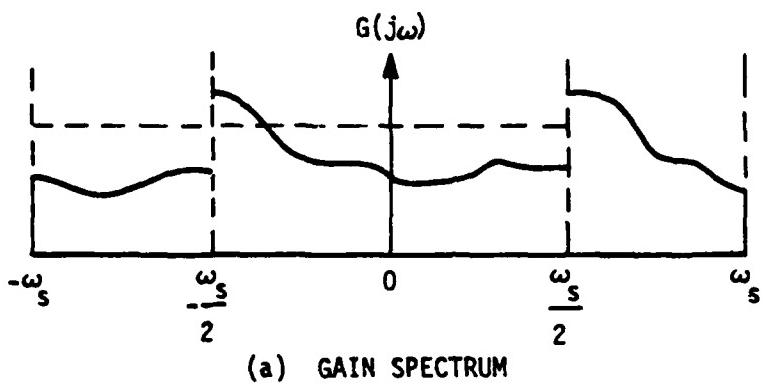
To achieve a set of real equalizer coefficients usually means to double the upper frequency bound of the signal samples (ω_s). When the upper frequency is doubled, the second half of the spectrum is copied from the original bandwidth with the proper polarity attached. Examples to illustrate these properties will be presented in the next section.

3.4 FFT ILLUSTRATIVE EXAMPLES

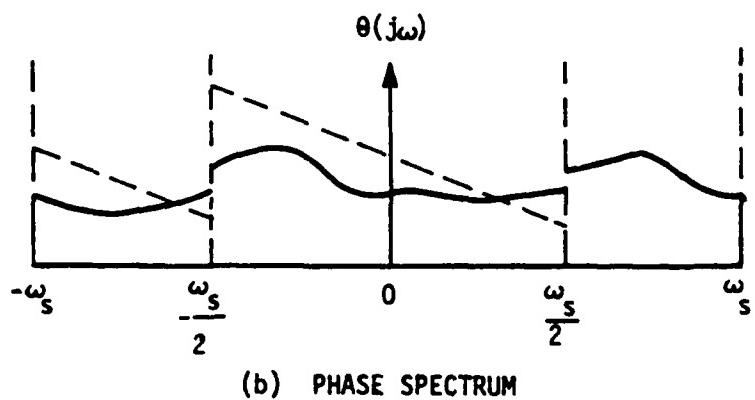
A few examples illustrates the Fourier transform approach to well defined $H(j\omega)$ will be given in this section.

3.4.1 Lowpass Filter

Figure 3-3 shows a specification for a lowpass transfer function with cutoff frequency set at 0.5 rad/sec and the upper frequency bound (ω_s) set at 2 rad/sec. The spectrum between $\omega_s/2$ to

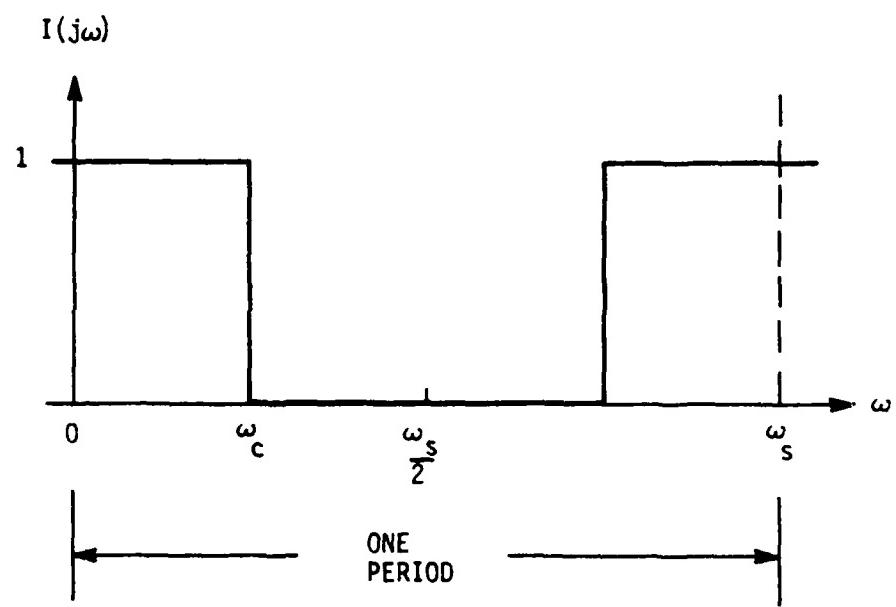


(a) GAIN SPECTRUM



(b) PHASE SPECTRUM

FIGURE 3-2. GAIN AND PHASE RESPONSE (GENERAL CASE - ASYMMETRIC)



$$\omega_s = 2 \text{ RAD/SEC}$$

$$\omega_c = 0.5 \text{ RAD/SEC}$$

$$Q(j\omega) = 0 \text{ FOR ALL } \omega$$

FIGURE 3-3. IDEAL RESPONSE OF A LOWPASS FILTER

ω_s is duplicated to provide an even function for the in-phase response $I(j\omega)$. The quad-phase response is set to zero.

The Fourier coefficients can be readily found to be

$$c_k = \frac{1}{k\pi} \sin(k\pi), \quad k = -N, -N+1, \dots N \quad (3-18)$$

$k \neq 0$ and $N = 8$

and $C_0 = 0.5$.

For the case $N = 8$, or 17-tap equalizer the response of the network can be plotted as shown in Figure 3-4.

Generally, the performance of such a filter indicates a passband ripple of 0.75 dB and a stopband rejection of approximately -20 dB. Direct truncation of the Fourier series leads to the well-known Gibbs phenomenon. The ripple, in generaly, cannot be reduced by simply including more taps as displayed by the 25 tap version shown in Figure 3-5.

The reduction of the passband ripple and stopband attenuation is later approached by finding a time-limited function whose Fourier transform best approximates a bandlimited function. This approach leads to the well-known Kaiser window expressed by:

$$\omega(K) = \frac{I_0(\beta \sqrt{1 - (K/N)^2})}{I_0(\beta)} \quad -N < K < N$$

where β is a constant ($1 < \beta < 10$)

I_0 is the modified Bessel function of order zero

N is half the number of taps

The constant β can be determined experimentally. Figure 3-6 shows the same 17 taps frequency response with Kaisier window. The

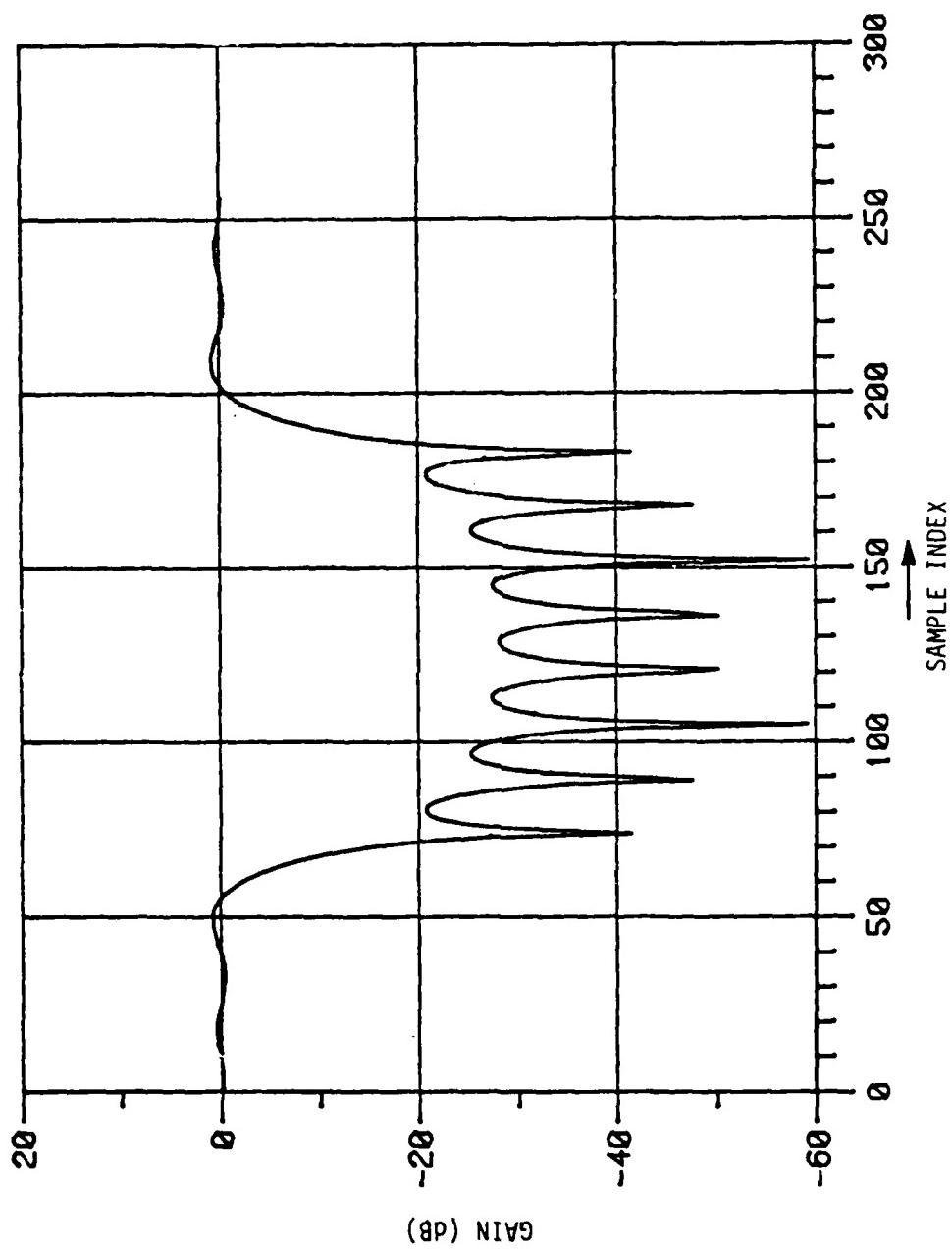


FIGURE 3-4. LOWPASS FILTER RESPONSE (17 TAPS) DIRECT TRUNCATION

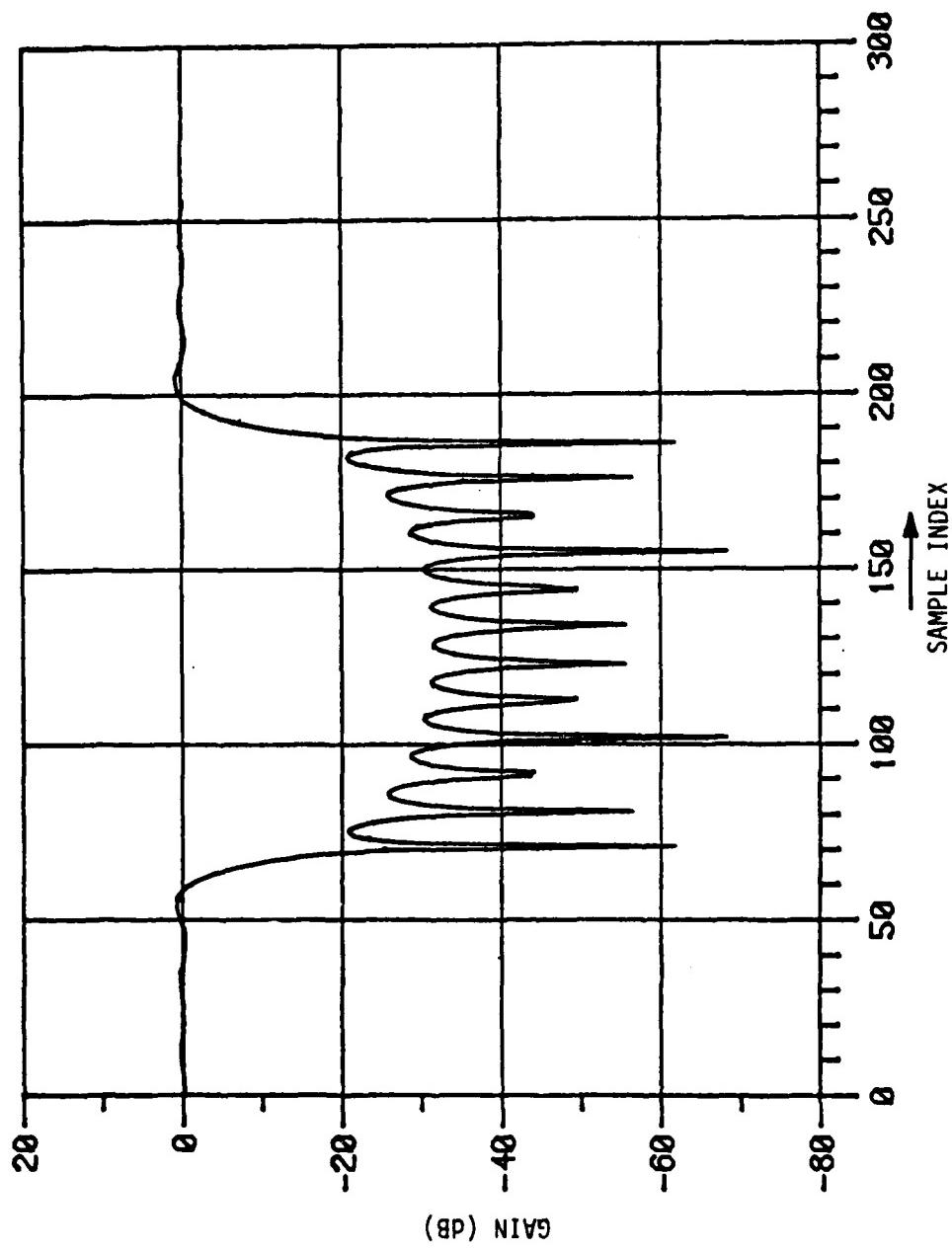


FIGURE 3-5. LOWPASS FILTER RESPONSE (25 Taps) DIRECTED TRUNCATION

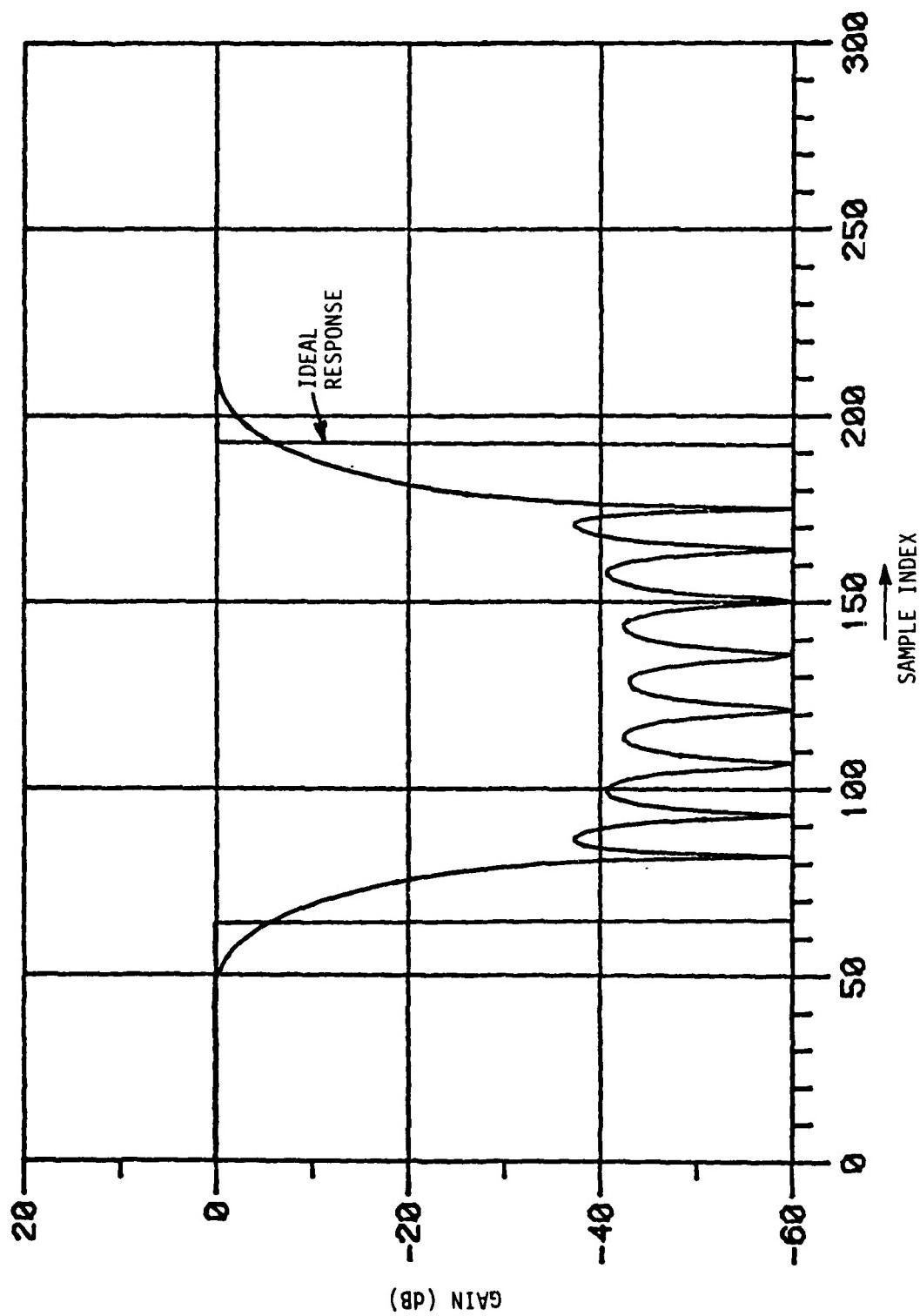


FIGURE 3-6. 17 - Tap LOWPASS FILTER WITH WINDOW

passband ripple is essentially vanished and the stopband rejection is reduced from -20 dB to -38 dB. Note that the windowing operation is a proper scale function applied to the impulse response of the filter. It does not change the hardware configuration of the filter.

3.4.2 A Differentiator

The response of a differentiator can be written by the equation

$$H(j\omega) = j\omega, \text{ for } -\omega_s/2 < \omega < \omega_s/2$$

This is the case that the in-phase response is zero and the quadrature is an odd function. As a result, the coefficient (or the impulse response) is real and odd functions; that is,

$$\begin{aligned} c_k &= \frac{2}{\omega_s} \int_0^{\omega_s/2} \omega \sin(k\omega T) d\omega \\ &= \int_0^1 \omega \sin(k\pi w) dw \text{ where } T = \frac{2\pi}{\omega_s} = \pi, \omega_s = 2 \\ &= -\frac{\cos(k\pi)}{k\pi}, k = -N, -N+1, -1, 1, \dots N \\ &\quad k = 0 \end{aligned}$$

where $k = 0$, $c_0 = 0$.

Figure 3-7 is the response of the filter with 17 taps and Figure 3-8 is the response with Kaiser window. The parameter β for the Kaiser window is set to 3 to reduce the ripple due to direct truncation of the Fourier series at $N = 8$.

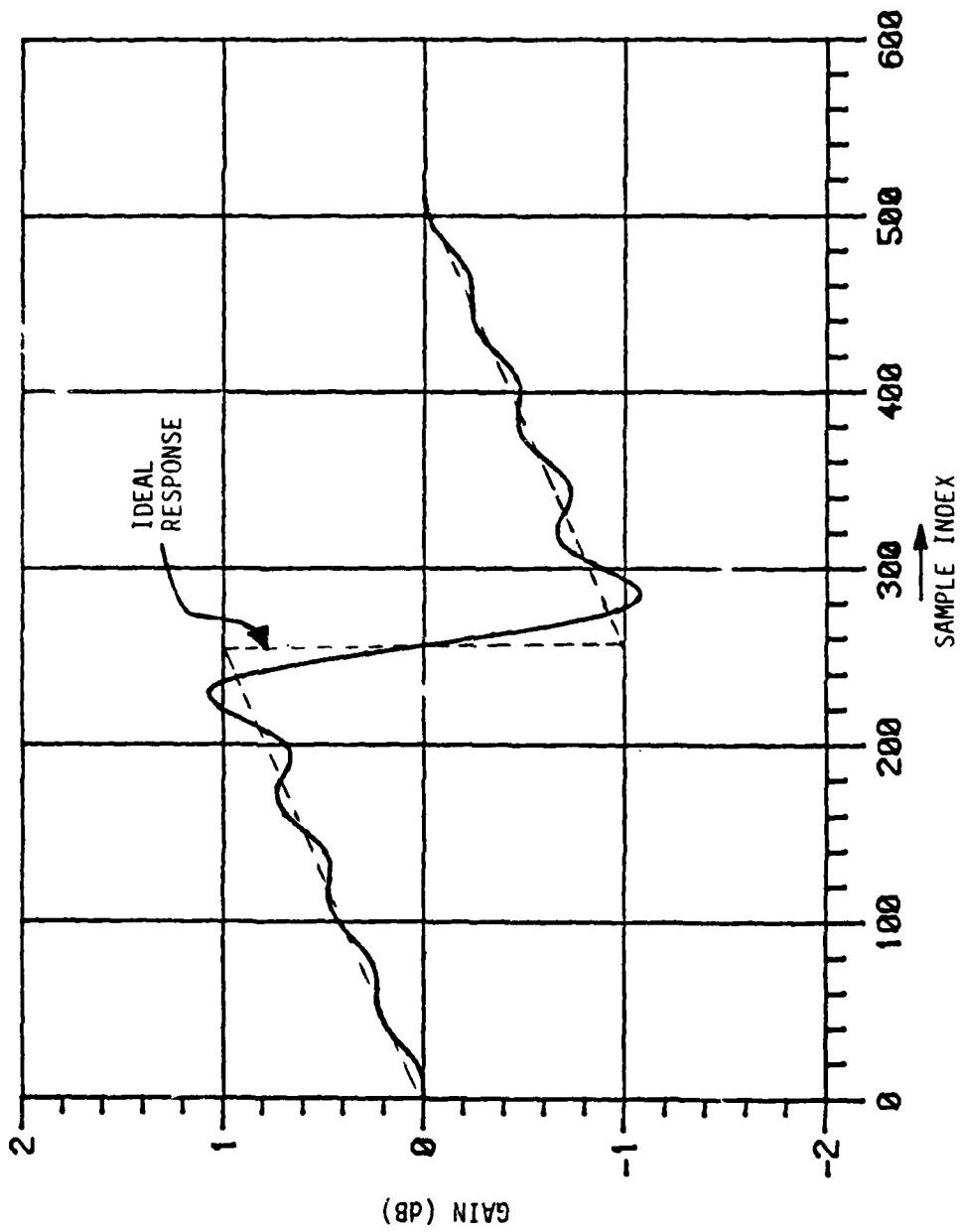


FIGURE 3-7. DIFFERENTIATOR RESPONSE (17 Taps) DIRECT TRUNCATION

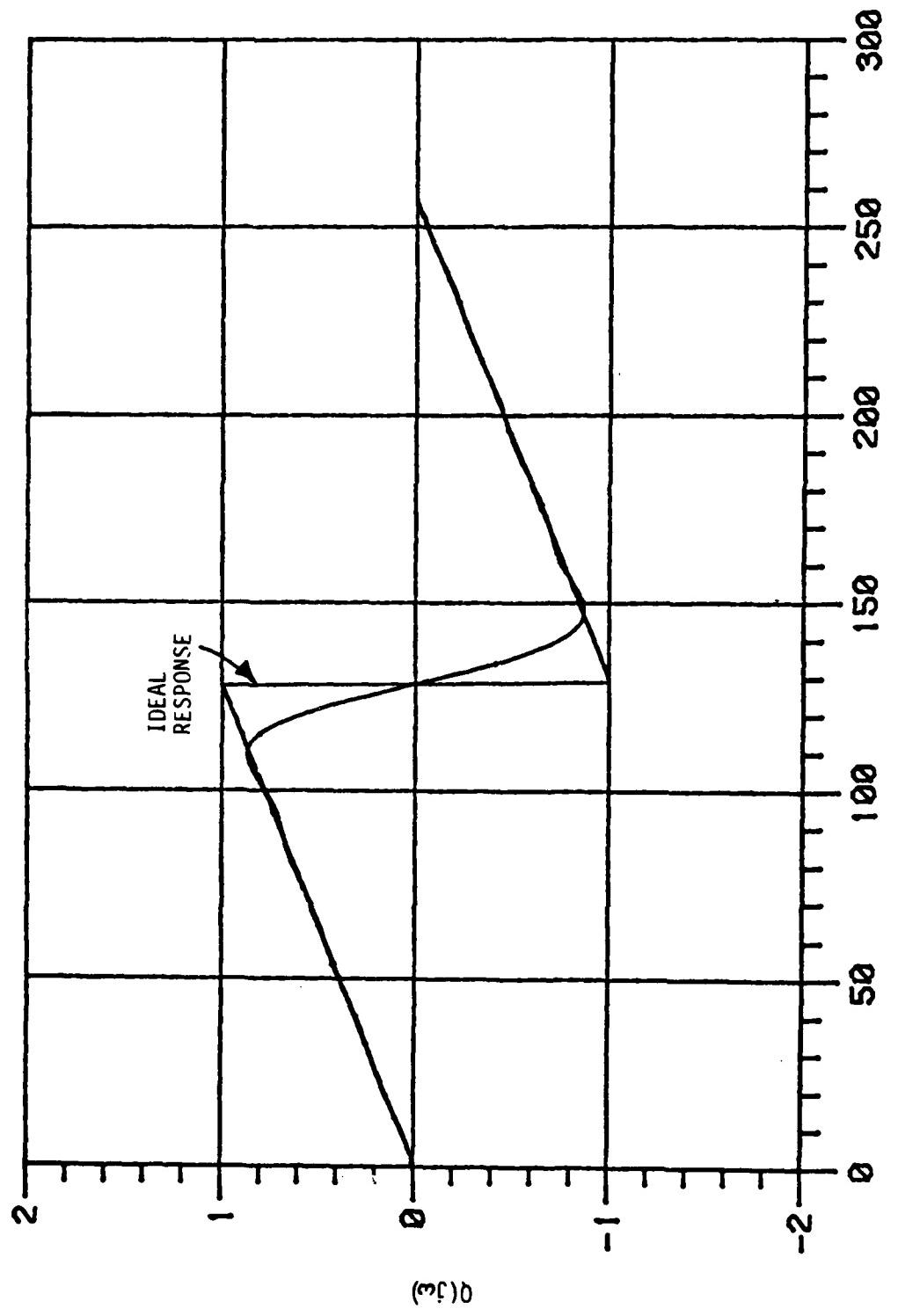


FIGURE 3-8. (17 Tap) DIFFERENTIATOR RESPONSE WITH WINDOW

3.4.3 Hilbert Transformer

The frequency response of a Hilbert transformer can be defined as

$$H(j\omega) = \begin{cases} -j, & 0 \leq \omega < \omega_s/2 \\ j, & \frac{\omega_s}{2} \leq \omega < \omega_s \end{cases}$$

The discrete Fourier transform can be expressed by the impulse response

$$h(n) = \begin{cases} \frac{\sin^2(n\pi/2)}{(n\pi/2)} & n \neq 0 \\ 0 & n = 0 \end{cases}$$

The comparison between a 17 tap filter and the ideal transform is shown in Figure 3-9.

3.4.4 Equalizer for an Arbitrary Function

The transfer function of an arbitrary frequency response

$$H(j\omega) = I(j\omega) + Q(j\omega)$$

over the band of interest is considered. Since the samples are not symmetrical in any sense, the resulting tap coefficients will be complex and asymmetrical. The matching of the ideal versus 17 tap equalizer is plotted in Figure 3-10 and the resulting complex taps are tabulated in Table 3-2. Note that the equalizer taps are complex:

$$c_k = x_k + j y_k, \quad k = 1, 2, \dots, 17$$

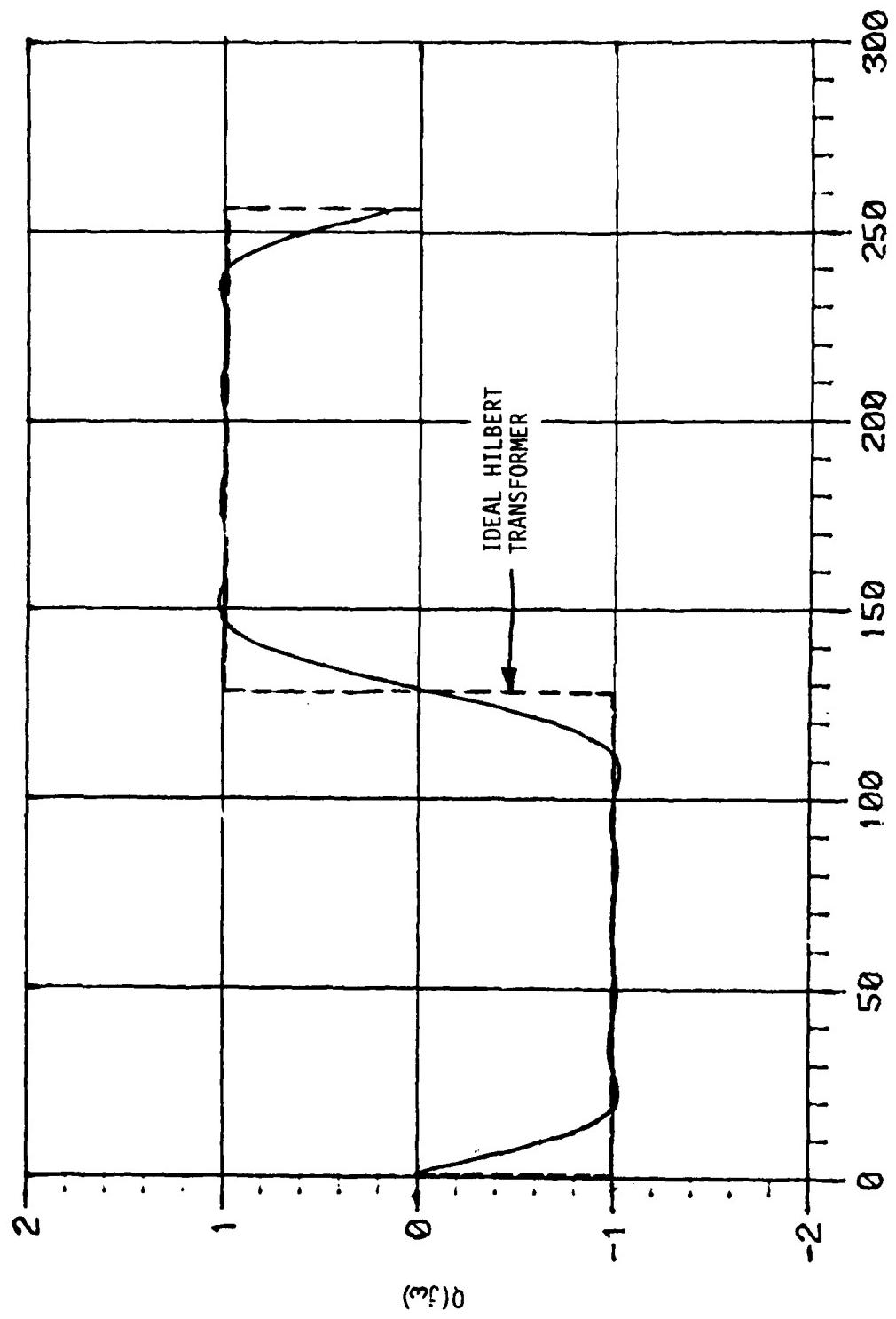


FIGURE 3-9. RESPONSE OF A (17 Tap) HILBERT TRANSFORMER (EXAMPLE 3)

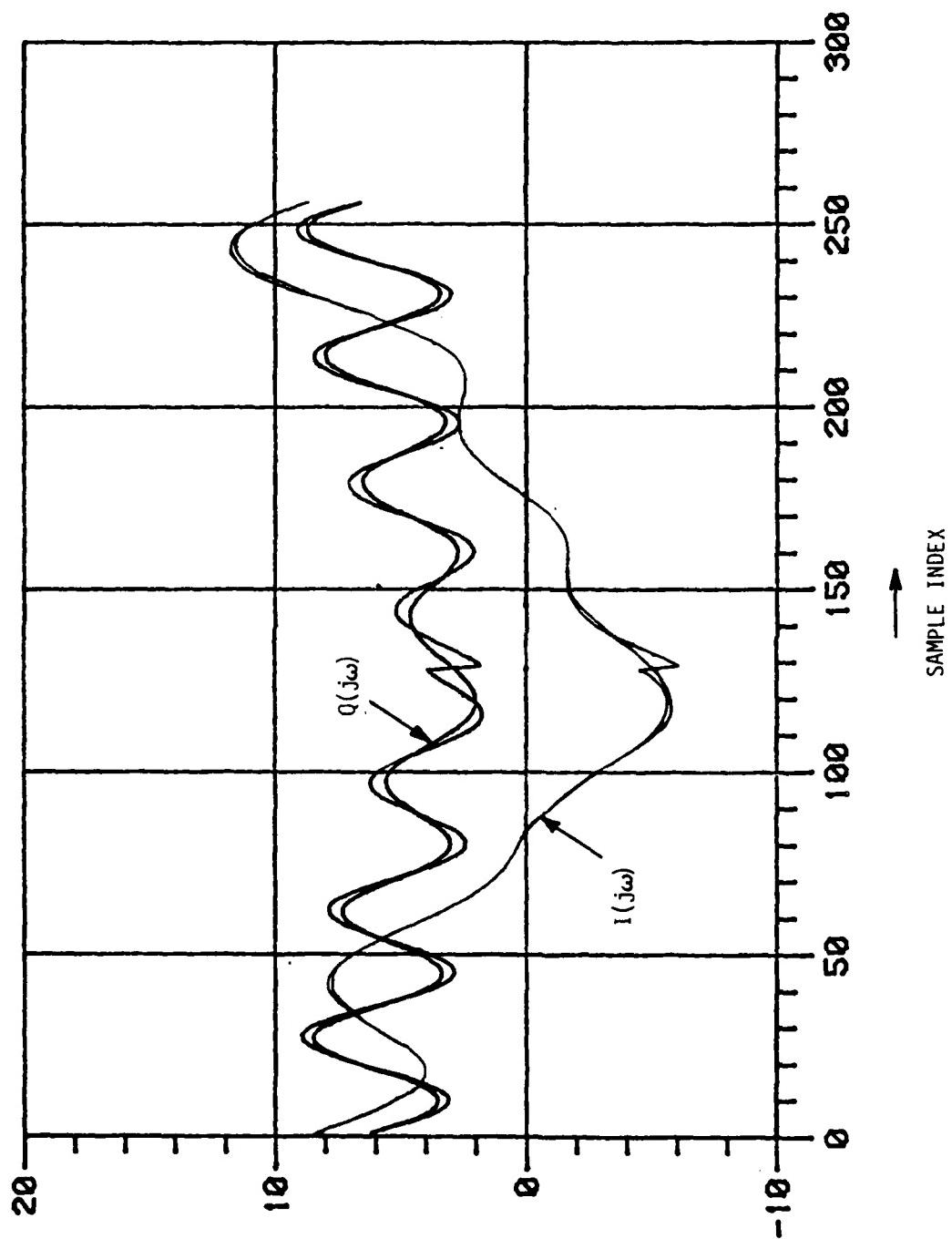


FIGURE 3-10. (17 Tap) EQUALIZER RESPONSE WITH AN ARBITRARY $I(j\omega)$ AND $Q(j\omega)$

and the gain and phase adjustment can be found by the transformation

$$g_k = 10 \times \log (x_k^2 + y_k^2)$$

$$\theta_k = \tan^{-1} (y_k/x_k)$$

TABLE 3-2. RESULTING EQUALIZER TAPS

| <u>Index</u> | <u>x_i</u> | <u>y_i</u> |
|--------------|-------------------------|-------------------------|
| 1 | 0.438043 | -0.036516 |
| 2 | 0.931036 | 0.043327 |
| 3 | -0.092596 | -0.064665 |
| 4 | 0.086571 | -0.686610 |
| 5 | -0.074379 | -0.578472 |
| 6 | 0.132042 | -0.643479 |
| 7 | -0.213581 | -0.047679 |
| 8 | 3.133260 | 0.643330 |
| 9 | 2.183238 | 4.936495 |
| 10 | 3.120918 | 0.712413 |
| 11 | -0.187885 | -0.225917 |
| 12 | 0.090602 | 0.764618 |
| 13 | -0.032419 | 0.508859 |
| 14 | -0.005370 | 0.732557 |
| 15 | 0.036480 | 0.031661 |
| 16 | -0.890202 | -0.018254 |
| 17 | -0.468842 | 0.016737 |

4. CONTROL PROGRAM

A Fast Fourier Transform (FFT) subroutine is employed to calculate the set tap coefficients for the equalizer. The equalizer taps are calculated in a recursive manner.

The input to the AMTE consists of a set of N complex correlations as a function of frequency. These samples can be expressed by the transfer function

$$H(j\omega_i) = I(\omega_i) + j Q(\omega_i), \quad i = 1, 2, \dots, N$$

where ω_i is the i^{th} radian frequency, $I(\omega_i)$ is the in-phase frequency response, and $Q(\omega_i)$ is the quad-phase frequency response, and N is the total number of sample points.

The output of the AMTE is a set of N_t equalizer taps. For the system at hand N_t is set equal to 17. These complex tap coefficients are obtained by a truncated Fourier series coefficients. The output tap coefficient will be presented by its magnitude setting (in dB's) and phase setting in degrees.

4.1 FLOW CHART

A simplified flow chart of the main routine is shown in Figure 4-1.

4.2 PROGRAM IMPLEMENTATION

The program is implemented on the RADC HP 2100, with the operating system configured on 2/6/81. The steps to be taken for execution of the program are:

After the logs on the HP 2100, the system will return the prompt sign ":". At this level, it is necessary to link the compiled version of the program \$ZA::45. To link, one gives the command:

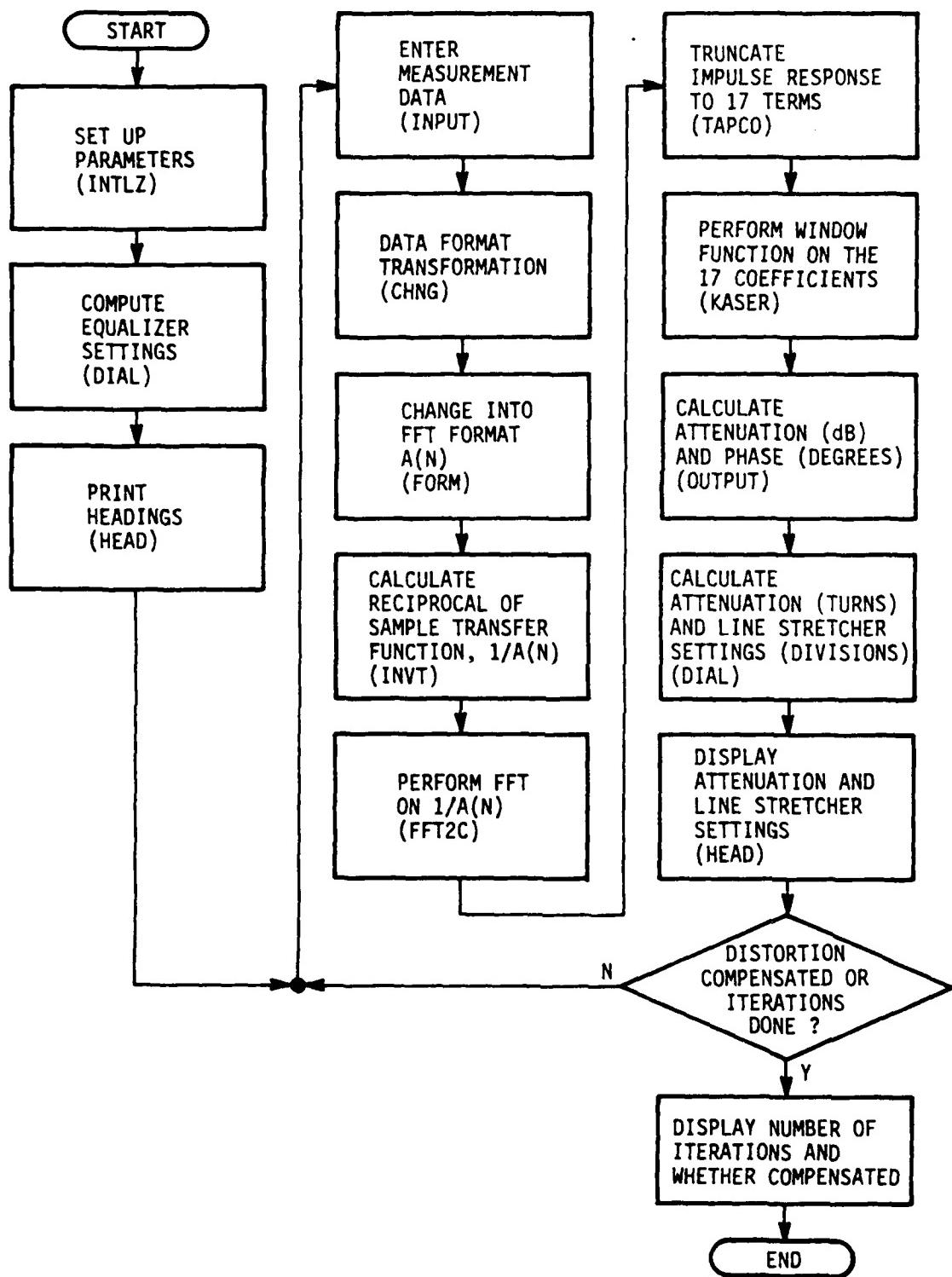


FIGURE 4-1. PROGRAM FLOW CKART

OF, AIL <CR>

Then after computer responds with ":" then type

RU, LOADR, XX <CR>

where XX is the peripheral number of the user's terminal (this may be optional) and <CR> is the carriage return key

The computer responds by giving a prompt of "/LOADR:". After this prompt, the user types:

RE, . ZA <CR>

The computer then lists the main line and the subroutines and functions called for by the user's program, in this case, \$ZA::45 while linking them together. When the computer is through linking these together, it comes back with another "/LOADR:". The user should then type

/E <CR>

The computer than links and lists on the user's terminal as it is linking, library routines and functions necessary for executing the user's program. The computer then comes back with:

"XX PAGES RELOCATED" "XX PAGES REQ'D"

"NO PAGES EMA" "NO PAGES MSEG"

"/LOADR:XX READY AT XX (date, time)"

"LOADR: \$END and it gives a ":" prompt

At the prompt, the user should run the program that has been loaded and linked, now called "AIL:. The command is:

"RU, AIL" <CR>

The computer then outputs any messages and data from the program, as it is running. The sequence of output should be:

INITIAL SETTINGS AT STEP 0 SHOULD BE...

ENTER THE FILE NAME

At this point, the user types in the name of the input file (containing a distorted sinusoid, if created by AT10 as described), for example we could use AD000, one input file from AT10; to use AD000 one types "AD000" (return)

after the message "ENTER THE FILE NAME".

The computer then prints out this message:

INTERMEDIATE SETTINGS AT STEP 1 ARE:

The computer then prints out the attenuator and the line stretcher values for the equalizer, then continues.

If the distortion has not been compensated in the first iteration, the program goes back to subroutine INPUT. The program repeats this loop 10 times, or until the distortion is less than a threshold set to be -45 dB, whichever comes first. When the program reaches the point of exiting the loop, it prints out either:

"AFTER 10 ITERATIONS DISTORTION CANNOT BE COMPENSATED"

or:

"DISTORTION COMPENSATED AFTER XX ITERATIONS"

then:

"AIL: STOP"

The computer then returns to the system level, and the user can perform other tasks, or sign off.

A sample run of the program implemented with input data is contained in Appendix 1.

4.3 COMPUTER SUBROUTINES

The following discussion includes the entry points, input arguments and output arguments of each subroutine in the AMTE program, and what the subroutines or functions accomplish.

1: Subroutine INTLZ (DMY1, DMY2, N, NTAP, BETA, IIO, IO, KSW)
initializes constants and arrays.

Input: None

Output: DMY1, DMY2, N, BETA, IO, KSW

DMY1 A Initial attenuator (dB) setting

DMY2 B Initial phase (degrees) setting

N Number of points to be transformed

NTAP Number of taps

BETA Constant used in KASER subroutine

IO Output device number

KSW Format Flag

KSW = 0: the data is expressed in decimal form

KSW = 1: the data is expressed in octal form

IIO Input device number (mag tape drive)

2: Subroutine DIAL (NTAP, DMY1, DMY2, X, Y)

This subroutine calculates attenuator and line stretcher settings.

Input: NTAP, DMY1, DMY2

DMY1, DMY2 - updated attenuation (dB) and phase (degrees)

Output: X, Y

X updated line stretcher (division) settings

Y updated attenuation (dB) settings

3: Subroutine Head (X,Y,NTAP, ISW, ICNT, IO)

This subroutine displays attenuator and line stretcher settings.

Input: X, Y, NTAP, ISW, ICNT, IO

X, Y line stretcher and attenuation settings

NTAP number of taps

ISW ISW = 0; sidelobe distortion < -45 dB

ISW = 1; at least one sidelobe > -45 dB

ICNT iteration counter

4. Subroutine INPUT (N, IBUF, IIO, IO, KSW)

INPUT defines input array of in-phase and quadrature-phase data.

Input: N, IIO, IO, KSW, file name

File Name file on which the data is stored

Output: IBUF

IBUF an array containing both I & Q data in octal form

5. Subroutine CHNG (N, IBUF)

This routine swaps the upper half of the FFT input array with the lower half.

Input: N, IBUF

Output: IBUF

6. Subroutine FORM (N, IBUF, A)

FORM will compute complex array A = I + jQ and also gain = $5 \log_{10} (I^2+Q^2)$ and phase = $\tan^{-1} (Q/I)$

Input: N, IBUF

Output: A

7. Subroutine INVT (N,A)

This subroutine computes the sequence to be equalized:

$$A_i = \frac{1}{A_i} \text{ where } i = 1, 2, 3, \dots, N$$

Input: N, A

Output: A

8. Subroutine FFT2C (A,M,IMK) computes the Fourier transform of the input array A

Input: M, A

Output: A

9. Subroutine TAPCO (N, A, NTAP, COEF, IO)

TAPCO truncates array A(N) into finite terms. The number of terms is defined as NTAP (number of taps) to specify an equalizer. The variable IO is a device number for the output which is normally computer-dependent. The resulting equalizer taps are stored in COEF (NTAP).

10. Subroutine KASER (NTAP, BETA, COEF, IO)

This subroutine applies the KAISER window function to the truncated Fourier transform output COEF (NTAP). A functional subroutine BESSL (X) is required to compute the window parameters. BESSL is the modified Bessel function of the first kind with zero order. The argument for the BESSL is X.

11. Subroutine OUTPT (DMYL1, DMYL2, COEF, NTAP, ISW)

Subroutine OUTPT computes updated attenuation (dB) and phase shift (degrees).

$$x_i = 20 \log_{10} (10^A); A = \frac{DMYL_i}{20} + 1$$

$$y_i = 20 \log_{10} (10^B); B = \frac{ATT_i}{20} + 1$$

$$\text{updated attenuation}_i = 20 \log_{10} (10^C)$$

$$\text{where } C = \frac{x_i + y_i}{20} + 1$$

and $i = 1, 2, \dots, N$

DMY1 - previous attenuation (dB)

ATT - present tap indication (dB)

$$\text{phase shift} = \sum_{i=1}^{i=N} \text{phase}_i$$

Input: DMY1, DMY2, COEF, NTAP

DMY1 - updated attenuation setting (dB)

DMY2 - updated phase shift setting (degrees)

ISW - ISW = 0; sidelobe distortion < -45 dB

ISW = 1; at least one sidelobe > -45 dB

12: Subroutine DIAL (NTAP, DMY1, DMY2, ISW, ICNT, IO)

DIAL was described previously.

13: Subroutine HEAD (X, Y, NTAP, ISW, ICNT, IO)

HEAD was described previously.

14: Subroutine END (ISW, ICNT, IO)

This subroutine will print a message depending on what the inputs are:

Input: ISW, ICNT, IO

Output: If ISW = 0, message is "Distortion compensated after so many iterations"

If ICNT = 10, message is "After 10 iterations distortion cannot be compensated"

15: Function ZLOG2: This function calculates log to the base 10 of the input quantity X. It takes the natural log (ALOG) of X and multiplies by Y, where $Y = 1/\log_e 10$.

16: Function ZN1: This calculates arctangent of input quantity (in radians).

4.4

COMPUTER PROGRAM LISTING

The following is a listing of the computer program:

```

0001  FTN4
0002  C      REVISED FILE 1/22/81
0003  C      PROGRAM AIL
0004  C      COMPLEX A(256),B(256),COEF(256)
0005  C      DIMENSION IBUF(256),IMY1(17),IMY2(17),X(17),Y(17)
0006  C      DIMENSION IWK(9)
0007  C      ICNT=0
0008  C      M=8
0009  C      INITIALIZE CONSTANTS
0010  C      CALL INTLZ(IMY1,IMY2,M,NTAP,BETA,IIO,IO,KSW)
0011  C      CALCULATE INITIAL ATTENUATOR AND LINE STRETCHER SETTING
0012  C      CALL DIAL(NTAP,IMY1,IMY2,X,Y)
0013  C      DISPLAY ATTENUATOR AND LINE STRETCHER SETTINGS
0014  C      CALL HEAD(X,Y,NTAP,ISW,ICNT,IO)
0015  DO 10 I= 1,10
0016  C      ICNT= I
0017  IF(ICNT.EQ.2) GO TO 20
0018  C      ENTER SAMPLE TRANSFER FUNCTION AS I AND Q DATA
0019  C      CALL INPUT(N,IBUF,IIO,IO,KSW)
0020  C      SHIFT DATA N/2, SAMPLES
0021  C      CALL CHNG(N,IBUF)
0022  C      COMPUTE TRANSFER FUNCTION A(N)=I(N)+JQ(N)
0023  C      CALL FORM(N,IBUF,A)
0024  C      COMPUTE EQUALIZER TRANSFER FUNCTION 1/A(N)
0025  C      CALL INVT(N,A)
0026  C      PERFORM FFT ON A
0027  C      CALL FFT2C(A,M,IWK)
0028  C      TRUNCATE THE IMPULSE RESPONSE TO 17 TERMS
0029  C      CALL TAPCO(N,A,NTAP,COEF,IO)
0030  C      PERFORM WINDOW FUNCTION ON TRUNCATED SERIES
0031  C      CALL KASER(NTAP,BETA,COEF)
0032  C      CALCULATE ATTENUATION (DB) AND PHASE SHIFT (DEGREES)
0033  C      CALL OUTPT(IMY1,IMY2,COEF,NTAP,ISW)
0034  C      CALCULATE ATTENUATION (TURNS) AND LINE STRETCHER SETTINGS
0035  C      CALL DIAL(NTAP,IMY1,IMY2,X,Y)
0036  C      DISPLAY ATTENUATION AND LINE STRETCHER SETTINGS
0037  C      CALL HEAD(X,Y,NTAP,ISW,ICNT,IO)
0038  IF(ISW.EQ.0)GO TO 20
0039  10 CONTINUE
0040  C      DISPLAY AFTER HOW MANY ITERATIONS DISTORTION WAS
0041  C      COMPENSATED, OR THAT IT WAS NOT COMPENSATED AFTER A
0042  C      GIVEN NUMBER OF ITERATIONS.
0043  20 CALL END(ISW,ICNT,IO)
0044  9998 WRITE(37,99980)
0045  99980 FORMAT(" AIL : STOP")
0046  END

```

```

0047 C
0048 C
0049 C      CALCULATE LOG TO THE BASE 10
0050 FUNCTION ZLOG1 (X)
0051 Y=0.4342944819
0052 IF (X.LE.0.) X=1.E-10
0053 ZLOG1=Y+ALOG (X)
0054 RETURN
0055 END
0056 C
0057 C      CALCULATE ARCTANGENT
0058 C
0059 FUNCTION ZN2 (Y,X)
0060 IF (X.EQ.0.) X=1.E-10
0061 PI=3.141592654
0062 Z=Y/X
0063 ZN2=ATAN (Z)
0064 IF (X.LT.0) ZN2=ZN2+PI
0065 C WRITE (37,976) Z,ZN2
0066 976 FORMAT (1X,E12.5,1X,E12.5)
0067 RETURN
0068 END
0069 C
0070 C
0071 C      CALCULATE BESSL FUNCTION OF THE FIRST KIND WITH 0 ORDER
0072 FUNCTION BESSL (X)
0073 Y=X/2
0074 DELTA=1E-8
0075 E=1.
0076 DE=1.
0077 DO 1 I=1,25
0078 DE=DE+Y/FLOAT (I)
0079 SDE=DE+DE
0080 E=E+SDE
0081 IF (E+DELTA.GT.SDE) GOTO 10
0082 1 CONTINUE
0083 10 BESSL=E
0084 RETURN
0085 END

```

```
0086 C
0087 C
0088 C      SWAP THE UPPER HALF OF THE ARRAY WITH THE LOWER HALF
0089      SUBROUTINE CHNG(N,IBUF)
0090      INTEGER IBUF(1),IBUF1(300)
0091      K1=(N+1)/2
0092      K2=K1-1
0093      K=N/2
0094      DO 10 I=K1,N
0095      J=I-K
0096      IBUF1(J)=IBUF(I)
0097      10 CONTINUE
0098      DO 20 I=1,K
0099      J=I+K1
0100      IBUF1(J)=IBUF(I)
0101      20 CONTINUE
0102      DO 30 I=1,N
0103      IBUF(I)=IBUF1(I)
0104      30 CONTINUE
0105      998 FORMAT (1X,12(I6,1X))
0106      ZX=1
0107      CALL TYPE(ZX)
0108      RETURN
0109      END
```

```

0110 C
0111 C      PERFORM POLYNOMIAL FUNCTION TO CONVERT FROM ATTENUATION (DB)
0112 C      TO ATTENUATION (DIAL TURNS) AND FROM PHASE SHIFT (DEGREES)
0113 C      TO LINE STRETCHER SETTINGS (DIVISIONS)
0114 C
0115 C      SUBROUTINE DIAL (NTAP,IMY1,IMY2,X,Y)
0116 C      DIMENSION R0(17),R1(17),R2(17),R3(17),
0117 C      IDMY1(1),IDMY2(1),X(1),Y(1)
0118 C      DATA R0/--.9102,-.7261,-.9251,-.6881,-.8607,-1.2297,
0119 C      1-1.1216,-1.1216,0.,-.8644,-.8416,-1.0381,-.9169,
0120 C      2-2.1413,-.8482,-1.0342,-.7343/
0121 C      DATA R1/-1.1166,-.07328,-.1116,-.06238,-.1026,-.12932,
0122 C      1-.1075,-.1075,0.,-.08205,-.07806,-.1176,-.0946,-.1399,
0123 C      2-.05173,-.1192,-.07771/
0124 C      DATA R2/-0.0009174,.001295,-.0003383,.001829,.0003621,
0125 C      1.00007163,-.0003624,-.0003624,0.,.0003096,-.0002962,
0126 C      2-.00003543,.000672,.0006742,.002387,-.001177,.001285/
0127 C      DATA R3/-0.0000383797,.00000377,-.00002436,.000011075,
0128 C      1-.0000212,-.000033318,-.00002773,-.00002773,0.,-.000025096,
0129 C      2-.00002957,-.0000273,-.000016696,-.00001571,.00001276,
0130 C      3-.00004344,-.000008216/
0131      DO 10 I=1,NTAP
0132      J=I
0133      IF (I.LE.8) J=9-I
0134      Y1=R0(I)+R1(I)*IMY1(J)+R2(I)*IMY1(J)*IMY1(J)
0135      Y2=R3(I)*IMY1(J)*IMY1(J)*IMY1(J)
0136      Y(I)=Y1+Y2
0137      X(I)=IMY2(J)*3.634/(360.*1.091)
0138      IF (Y(I).LT.0.0) Y(I)=0.0
0139      IF (Y(I).GT.10.0) Y(I)=10.0
0140      IF (X(I).LT.0.0) X(I)=0.0
0141      IF (X(I).GT.11.0) X(I)=11.0
0142      10 CONTINUE
0143 C      WRITE (37,979) (X(I),I=1,NTAP)
0144 C      WRITE (37,979) (Y(I),I=1,NTAP)
0145 979 FORMAT (1X,4(E12.5,1X,E12.5,1X))
0146 ZX=2
0147 CALL TYPE (ZX)
0148 RETURN
0149 END

```

```

0150 C
0151 C
0152 C      PRINT OUT WHETHER DISTORTION IS COMPENSATED AFTER THE
0153 C      LAST ITERATION
0154 C      SUBROUTINE END(ISW,ICNT,IO)
0155 IF (ISW.EQ.0) GO TO 10
0156 WRITE(37,20) ICNT
0157 20 FORMAT(1X,3X,5HAFTER,I3,3I1H ITERATIONS DISTORTION CAN NOT,
0158 114HBE COMPENSATED,1X)
0159 GO TO 30
0160 10 CONTINUE
0161 ICNT=ICNT-1
0162 WRITE(37,40) ICNT
0163 40 FORMAT(1X,3X,28HDISTORTION COMPENSATED AFTER,I2,11HITERATIONS
0164 30 CONTINUE
0165 ZX=3
0166 CALL TYPE(ZX)
0167 RETURN
0168 END
0169 C
0170 C
0171 C
0172 C      SUBROUTINE FORM(N,IBUF,A)
0173 COMPLEX A(1)
0174 DIMENSION IBUF(1)
0175 C      COMPUTE COMPLEX ARRAY A=I+JQ
0176 DO 10 I=1,N
0177 IA1=IBUF(I)/256
0178 IB1=IBUF(I)-256*IA1
0179 IF (IA1.GE.128) IA1=IA1-256
0180 IF (IB1.GE.128) IB1=IB1-256
0181 XI=FLOAT(IA1)/128.
0182 XQ=FLOAT(IB1)/128.
0183 A(I)=CMPLX(XI,XQ)
0184 10 CONTINUE
0185 998 FORMAT (1X,4(E12.5,1X,E12.5,1X))
0186 ZX=4
0187 CALL TYPE(ZX)
0188 RETURN
0189 END
0190 C

```

```

0191 C
0192      SUBROUTINE HEAD  (X,Y,NTAP,ISW,ICNT,IO)
0193      DIMENSION X(1),Y(1),ZR(17)
0194      DATA ZR/4H1 A=,4H2 A=,4H3 A=,4H4 A=,4H5 A=,4H6 A=,4H7 A=,
0195          14H8 A=,4H M =,4H1 B=,4H2 B=,4H3 B=,4H4 B=,4H5 B=,4H6 B=,
0196          14H7 B=,4H8 B=/
0197      WRITE(37,145)
0198      145 FORMAT(1H1)
0199      ICNT1=ICNT+1
0200      GO TO (10,20,20,20,20,20,20,20,20,30) ICNT1
0201      10  CONTINUE
0202      WRITE(37,150) ICNT
0203 C      DISPLAY ATTENUATION AND LINE STRETCHER SETTINGS
0204      150 FORMAT(1,18X,25HINITIAL SETTINGS AT STEP ,I1,11H SHOULD BE:
0205      GO TO 205
0206      20  CONTINUE
0207      ISW1=ISW+1
0208      GO TO (30,200) ISW1
0209      200 CONTINUE
0210      WRITE(37,155) ICNT
0211      155 FORMAT(1,18X,29HINTERMEDIATE SETTINGS AT STEP,I2,5H ARE: )
0212      GO TO 205
0213      30  CONTINUE
0214      WRITE(37,160) ICNT
0215      160 FORMAT(1,21X,23HFINAL SETTINGS AT STEP ,I2,5H ARE: )
0216      205 CONTINUE
0217      WRITE(37,965)
0218      965 FORMAT(1/10X,17HATTENUATOR (TURNS),31X,19HLINE STRETCHER (DIV
0219      DO 210 I=1,NTAP
0220      WRITE(37,170) ZR(I),Y(I),ZR(I),X(I)
0221      170 FORMAT(10X,A4,F6.3,34X,A4,F4.1)
0222      210 CONTINUE
0223      ZX=5
0224      CALL TYPE (ZX)
0225      RETURN
0226      END
0227 C

```

```
0228 C
0229      SUBROUTINE INPUT(N,IBUF,IIO,IO,KSW)
0230      DIMENSION IDC8(256),NAM(3),IBUF(256)
0231      DIMENSION IBUF0(128),IBUF1(128)
0232      WRITE(37,10)
0233      10 FORMAT(1X,' ENTER THE FILE NAME ')
0234      READ(37,15) NAM
0235      15 FORMAT(3A2)
0236      IL=N
0237      CALL OPEN(IDC8,IERR,NAM)
0238      IF(IERR.LT.0)GO TO 900
0239 C      ENTER DATA IN OCTAL FORMAT
0240      CALL READF(IDC8,IERR,IBUF0)
0241      CALL READF(IDC8,IERR,IBUF1)
0242      IF(IERR.LT.0)GO TO 910,
0243      CALL CLOSE(IDC8,IERR)
0244 C      FILL ARRAY WITH IN-PHASE AND QUADRATURE-PHASE COMPONENTS
0245      DO 60 J=1,128
0246      IBUF(J)=IBUF0(J)
0247      60 CONTINUE
0248      DO 70 K=1,128
0249      IBUF(K+128)=IBUF1(K)
0250      70 CONTINUE
0251      998 FORMAT(1X,12(I6,1X))
0252      GO TO 999
0253      900 WRITE(37,30) IERR
0254      30 FORMAT(1X," FMP ERROR ",I4)
0255      GO TO 999
0256      910 WRITE(37,20)
0257      20 FORMAT(1X," ERROR READING THE FILE ")
0258      999 ZX=6
0259      CALL TYPE(ZX)
0260      RETURN
0261      END
0262 C
```

```
0263 C
0264 C           INITIALIZE CONSTANTS AND ARRAY
0265 C           SUBROUTINE INTLZ(DMY1,DMY2,N,NTAP,BETA,IIO,KSW)
0266 C           DIMENSION DMY1(1),DMY2(1),A(17),B(17)
0267 C           DATA A/-59.964,-59.964,-51.072,-56.743,-77.661,-60.551,
0268 C                  1-72.714,-57.353,0.,-58.449,-62.143,-55.373,-57.741,
0269 C                  2-54.419,-69.504,-57.047,-58.965/
0270 C           DATA B/659.23,756.49,810.53,983.44,162.1,399.86,
0271 C                  1670.03,859.16,443.09,129.68,399.86,561.96,778.1,
0272 C                  254.04,151.3,345.82,670.03/
0273 C           N=256
0274 C           NTAP=17
0275 C           DO 10 I=1,NTAP
0276 C           DMY1(I)=A(I)
0277 C           DMY2(I)=B(I)
0278 10    CONTINUE
0279 C           BETA=1.0
0280 C           IIO=37
0281 C           IO=37
0282 C           FOR DECIMAL I&Q,KSW=0
0283 C           FOR OCTAL I&Q,KSW=1
0284 C           KSW=1
0285 C           ZX=7
0286 C           CALL TYPE(ZX)
0287 C           RETURN
0288 C           END
0289 C
```

```

0290 C
0291 C      CALCULATE THE RECIPROCAL OF THE TRANSFER FUNCTION
0292 SUBROUTINE INV1(N,A)
0293 COMPLEX A(1)
0294 DO 10 I=1,N
0295 A(I)=1./ (A(I)+FLOAT(N))
0296 10 CONTINUE
0297 C      WRITE (37,998) (A(I),I=1,N)
0298 998 FORMAT (1X,4(1X,E12.5,1X,E12.5,1X))
0299 ZX=8
0300 CALL TYPE(ZX)
0301 RETURN
0302 END
0303 C
0304 C
0305 C      APPLY KAISER WINDOW FUNCTION TO SMOOTH OUT THE RIFFLE DUE
0306 C      TO TRUNCATION OF THE FOURIER SERIES
0307 SUBROUTINE KASER(N,B,C)
0308 COMPLEX C(1)
0309 IF (B.EQ.0.0) GO TO 9999
0310 NV2=(N+1)/2
0311 DO 10 I=1,N
0312 Z2=FLOAT(I-NV2)/FLOAT(N/2)
0313 Z3=B*SORT(1.-Z2*Z2)
0314 C(I)=C(I)+BESSL(Z3)/BESSL(B)
0315 10 CONTINUE
0316 C      WRITE (37,979) (C(I),I=1,N)
0317 979 FORMAT (1X,4(1X,E12.5,1X,E12.5))
0318 9999 ZX=9
0319 CALL TYPE(ZX)
0320 RETURN
0321 END
0322 C

```

```

0323 C
0324      SUBROUTINE OUTPT(DMY1,DMY2,COEF ,NTAP,ISW)
0325      COMPLEX COEF(1)
0326      DIMENSION DMY1(1),DMY2(1),ATT(17),PHS(17)
0327      DO 10 I=1,NTAP
0328      XR=REAL(COEF(I))
0329      XI=AIMAG(COEF(I))
0330      C      COMPUTE ATTENUATION OF DISTORTION
0331      AA=XR*Xr+XI*XI
0332      ATT(I)=10.*ZLOG1(AA)
0333      C      COMPUTE THE PHASE SHIFT OF TAP COEFFICIENTS
0334      PHS(I)=CNE(XI,XR)*45./ATAN(1.)
0335      ZZ=CNE(XI,XR)
0336      C      WRITE (37,978) PHS(I),ZZ
0337      978      FORMAT (1X,E12.5,1X,E12.5)
0338      10      CONTINUE
0339      DO 20 I=1,NTAP
0340      ATT(I)=ATT(I)-ATT(9)
0341      PHS(I)=PHS(I)-PHS(9)
0342      20      CONTINUE
0343      ISW=0
0344      NTAP1=NTAP-1
0345      DO 30 I=1,NTAP1
0346      J=I
0347      IF (I.GE.9) J=I+1
0348      IF (ATT(J).LE.-45.) GO TO 15
0349      ISW=1
0350      GO TO 30
0351      15      CONTINUE
0352      ISW=ISW
0353      30      CONTINUE
0354      IF (ISW.EQ.0) GO TO 40
0355      DO 50 I=1,NTAP
0356      X=20.*ZLOG1((10.*((DMY1(I)-20.))+1))
0357      Y=20.*ZLOG1((10.*((ATT(I)/20.))+1))
0358      DMY1(I)=20.*ZLOG1((10.*((X+Y)/20.))-1)
0359      DMY2(I)=DMY2(I)+PHS(I)
0360      50      CONTINUE
0361      40      CONTINUE
0362      WRITE (37,996)
0363      996      FORMAT (1X,14HATTENUATOR (DB),37X,19HLINE STRETCHER (DEG),/)
0364      *886      ZX=10
0365      DO 881 I=1,NTAP
0366      WRITE (37,977) DMY1(I),DMY2(I)
0367      977      FORMAT (1X,E12.5,37X,E12.5)
0368      881      CONTINUE
0369      979      FORMAT (1X,4(1X,E12.5,1X,E12.5))
0370      CALL TYPE(ZX)
0371      RETURN
0372      END
0373      C

```

```
0374 C
0375 C      SUBROUTINE TAPCO(N,A,NTAP,COEF,IO)
0376 C      COMPLEX A(1),COEF(1)
0377 C      NV2=(NTAP+1)/2
0378 C      NV21=N+NV2+1
0379 C      NV1=NV2+1
0380 C      TRUNCATE THE ARRAY A(N) INTO A GIVEN NUMBER(NTAP) OF
0381 C      TERMS
0382 DO 20 I=1,NV2
0383 J=NV2-I+1
0384 COEF(I)=A(J)
0385 20 CONTINUE
0386 C      OBTAIN THE UPPER HALF OF THE COEFFICIENTS CENTERED
0387 C      AROUND (NTAP+1)/2
0388 DO 30 I=NV1,NTAP
0389 J=NV21-I
0390 COEF(I)=A(J)
0391 30 CONTINUE
0392 C      WRITE (37,979) (COEF(I),I=1,NTAP)
0393 979 FORMAT (1X,4(1X,E12.5,1X,E12.5))
0394 ZX=11
0395 CALL TYPE(ZX)
0396 RETURN
0397 END
```

```

0398 C
0399 C
0400      SUBROUTINE FFT2C (A,M,IWK)
0401      INTEGER M,IWK(1)
0402      COMPLEX A(1)
0403 C
0404 C
0405      INTEGER I,ISP,J,JJ,JSP,K,K0,K1,K2,K3,KB,KN,MK,MM,MP,N,
0406      1 N4,N8,N2,LM,NN,JK
0407      REAL RAD,C1,C2,C3,S1,S2,S3,CK,SK,SQ,A0,A1,A2,A3,
0408      1 B0,B1,B2,B3,TWOPi,TEMP,
0409      2 ZERO,ONE,Z0(2),Z1(2),Z3(2)
0410      2 ZERO,ONE,Z0(2),Z1(2),Z3(2),Z2(2)
0411      COMPLEX ZA0,ZA1,ZA2,ZA3,AK2
0412      EQUIVALENCE (ZA0,Z0(1)),(ZA1,Z1(1)),(ZA2,Z2(1)),
0413      1 (ZA3,Z3(1)),(A0,Z0(1)),(B0,Z0(2)),(A1,Z1(1)),
0414      2 (B1,Z1(2)),(A2,Z2(1)),(B2,Z2(2)),(A3,Z3(1)),
0415      3 (B3,Z3(2))
0416      DATA S0/.707106781/
0417      DATA SK/.382683432/
0418      DATA CK/.923879533/
0419      DATA TWOPi/6.28318531/
0420      DATA ZERO/0.0/,ONE/1.0/
0421      MP = M+1
0422      N = 2**M
0423      IWK(1) = 1
0424      MM=(M/2)*2
0425      KN = N+1
0426      DO 5 I=2,MP
0427      IWK(I) = IWK(I-1)+IWK(I-1)
0428      5 CONTINUE
0429      RAD = TWOPi/N
0430      MK = M - 4
0431      KB = 1
0432      IF (MM .EQ. M) GO TO 15
0433      K2 = KN
0434      K0 = IWK(MM+1) + KB
0435      10 K2 = K2 - 1
0436      K0 = K0 - 1
0437      AK2 = A(K2)
0438      A(K2) = A(K0) - AK2
0439      A(K0) = A(K0) + AK2
0440      IF (K0 .GT. KB) GO TO 10
0441      15 C1=ONE
0442      S1 = ZERO
0443      JJ = 0
0444      K = MM - 1

```

```

0445      J = 4
0446      IF (K .GE. 1) GO TO 30
0447      GO TO 70
0448      20 IF (IWK(J) .GT. JJ) GO TO 25
0449      JJ = JJ - IWK(J)
0450      J = J - 1
0451      IF (IWK(J) .GT. JJ) GOTO 25
0452      JJ=JJ-IWK(J)
0453      J=J-1
0454      K = K + 2
0455      GO TO 20
0456      25 JJ = IWK(J) + JJ
0457      J = 4
0458      30 ISP = IWK(K)
0459      IF (JJ .EQ. 0) GO TO 40
0460      C2 = JJ * ISP * RAD
0461      C1 = COS(C2)
0462      S1 = SIN(C2)
0463      35 C2 = C1 * C1 -S1 * S1
0464      S2 = C1 * (S1 + S1)
0465      E3 = C2 * C1 -S2 * S1
0466      S3= C2 * S1 + S2 * C1
0467      40 JSP = ISP + KB
0468      C   WRITE (37,997) S1,S2,S3
0469      C   WRITE (37,997) C1,C2,C3
0470      DO 50 I = 1 , ISP
0471      K0 = JSP - I
0472      K1 = K0 + ISP
0473      K2 = K1 + ISP
0474      K3 = K2 + ISP
0475      ZA0 = A(K0)
0476      ZA1 = A(K1)
0477      ZA2 = A(K2)
0478      ZA3 = A(K3)
0479      IF (S1 .EQ. ZERO) GO TO 45
0480      TEMP = A1

```

```

0481      A1 = A1 + C1 - B1 + S1
0482      B1 = TEMP + S1 + B1 + C1
0483      TEMP = A2
0484      A2 = A2 + C2 - B2 + S2
0485      B2 = TEMP + S2 + B2 + C2
0486      TEMP = A3
0487      A3 = A3 + C3 - B3 + S3
0488      B3 = TEMP + S3 + B3 + C3
0489      45   TEMP = A0 + A2
0490      A2 = A0 - A2
0491      A0 = TEMP
0492      TEMP = A1 + A3
0493      A3 = A1 - A3
0494      A1 = TEMP
0495      TEMP = B0 + B2
0496      B2 = B0 - B2
0497      B0 = TEMP
0498      TEMP = B1 + B3
0499      B3 = B1 - B3
0500      B1 = TEMP
0501      AZ1=A0+A1
0502      AZ2=B0+B1
0503      AZ3=A0-A1
0504      AZ4=B0-B1
0505      AZ5=A2-B3
0506      AZ6=B2+A3
0507      AZ7=A2+B3
0508      AZ8=B2-A3
0509      997   FORMAT (1X,4(E12.5,1X))
0510      A(K0) = CMPLX(AZ1,AZ2)
0511      A(K1) = CMPLX(AZ3,AZ4)
0512      A(K2) = CMPLX(AZ5,AZ6)
0513      A(K3) = CMPLX(AZ7,AZ8)
0514      999   FORMAT (1X,'A COEFFICIENTS')
0515      50    CONTINUE
0516      C     WRITE (37,998) A(K0),A(K1),A(K2),A(K3)
0517      C     WRITE (37,995) K0,K1,K2,K3
0518      995   FORMAT (1X,4(I4,1X))
0519      998   FORMAT(1X,4(E12.5,1X,E12.5,1X))
0520      IF (K .LE. 1) GO TO 55

```

0521 K = K - 2
0522 GO TO 30
0523 55 KB = K3 + ISP
0524 IF (KN .LE. KB) GO TO 70
0525 IF (J .NE. 1) GO TO 60
0526 K = 3
0527 J = MK
0528 GO TO 20
0529 60 J = J - 1
0530 C2 = C1
0531 IF (J .NE. 2) GO TO 65
0532 C1 = C1 ◆ CK + S1 ◆ SK
0533 S1 = S1 ◆ CK - C2 ◆ SK
0534 GO TO 35
0535 65 C1 = (C1-S1) ◆ SQ
0536 S1 = (C2 + S1) ◆ SQ
0537 GO TO 35
0538 70 CONTINUE
0539 C WRITE (37,998) (A(KZ),KZ=1,256)
0540 IF (M .LE. 1) GO TO 9005
0541 MP = M + 1
0542 JJ = 1
0543 IWK(1) = 1
0544 DO 75 I = 2,MP
0545 IWK(I) = IWK(I-1)♦2
0546 75 CONTINUE
0547 N4 = IWK(MP-2)
0548 IF (M .GT. 2) N8 = IWK(MP-3)
0549 N2 = IWK(MP-1)
0550 LM = N2
0551 NN = IWK(MP) + 1
0552 MP = MP - 4
0553 J = 2

```

0554 80    JK = JJ + N2
0555          AK2 = A(J)
0556          A(J) = A(JK)
0557          A(JK) = AK2
0558          J = J+1
0559          IF (JJ .GT. N4) GO TO 85
0560          JJ = JJ + N4
0561          GO TO 105
0562 85    JJ = JJ - N4
0563          IF (JJ .GT. N8) GO TO 90
0564          JJ = JJ + N8
0565          GO TO 105
0566 90    JJ = JJ - N8
0567          K = MP
0568 95    IF (IWK(K) .GE. JJ) GO TO 100
0569          JJ = JJ - IWK(K)
0570          K = K - 1
0571          GO TO 95
0572 100   JJ = IWK(K) + JJ
0573 105   IF (JJ .LE. J) GO TO 110
0574          K = NN - J
0575          JK = NN - JJ
0576          AK2 = A(J)
0577          A(J) = A(JJ)
0578          A(JJ) = AK2
0579          AK2 = A(K)
0580          A(K) = A(JK)
0581          A(JK) = AK2
0582 110    J = J + 1
0583          IF (J .LE. LM) GO TO 80
0584 9005   ZX=12
0585          CALL TYPE(ZX)
0586 C      WRITE (37,998) (A(KZ),KZ=1,256)
0587          RETURN
0588          END
0589 C
0590 C
0591          SUBROUTINE TYPE(ZX)
0592 C      WRITE(37,20) ZX
0593 20    FORMAT(1,1 SUBROUTINE ENTERED 1,F4.1)
0594          RETURN
0595          END

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4.5 COMPUTER SOFTWARE VERIFICATION

To assure that the software works properly, the following verification procedure has been established. Before running the program on real data, it is recommended that the program be run on an idealized, sinusoidal waveform with slight distortion added.

Two cases of distortion will be introduced; the first one involves amplitude only, and the second one involves phase only. The distortions are presented as sinusoids of various amplitudes but always small enough so as to permit the use of the paired echo theory concepts to be valid. Also, the period of the sinusoid is always harmonically related to the bandwidth of the equalizer network and as such is consistent with the concept of representing the distortion as a Fourier series.

The test cases of distortion are separated into two groups, one of which assumes only amplitude distortion and the other of which assumes only phase distortion, but of varying levels. The FFT presents the coefficients for the taps which in effect represent the amplitude and phase of the echo associated with each tap. These coefficients are then compared to the calculated values based on the paired echo theory.

CASE 1: A sinusoidal amplitude distortion of various peak to peak values.

$$|G| = 10 \log_{10} \sqrt{I^2+Q^2} = 5 \log_{10} (I^2+Q^2) = \text{amplitude}$$

$$\theta = \tan^{-1} \frac{Q}{I} = \text{phase}$$

To simplify, we consider the effects of only amplitude distortions so that assuming no phase distortion and letting $Q = 0$ we get

$$|G| = 5 \log_{10} I^2 = 10 \log_{10} I$$
$$\theta = \tan^{-1} \left(\frac{Q}{I} \right) = 0$$

Since a sinusoidal distortion is needed:

$$\frac{\sin(\Delta X N)}{K} - 1 = 10 \log_{10} I$$

where

ΔX = incremental frequency

N = number of points

K = scale factor (for $K = 1$, numerator goes 0 to -2 or 2 dB)

and $10 \log I$ represents the distortion level in dB (peak-to-peak).

In order to fit the RADC data form so that $-128 \leq I < 128$, we multiply the given values of I by 128.

TEST 1: Amplitude distortion, 0.5 dB peak-to-peak with first echo pair

$$-0.5 = \frac{\sin(\Delta X N) - 1}{K} = 10 \log_{10} I \text{ therefore } K = 4$$

For 215 points in 2π radians or 360° , there $\Delta X = \frac{360^\circ}{215}$ and $0 \leq N \leq 214*$

$$I = 10 \left[\frac{\sin(\Delta X N) - 1}{40} \right]$$

From the test run we get the first echo peak value distortion to be -30.44 dB. Analytically (for small amp distortion) we have:

*Note that the number of sample points is not germane to the analysis (as long as it is a large number) and relates only to the expected number of samples to be used. We later change this to 256 points.

$$20 \log_{10} \left(1 + \frac{a_1}{a_0}\right) = \text{amplitude ripple in dB (peak value)}$$

for $\frac{a_1}{a_0} \ll 1$; $\frac{1}{2} \frac{a_1}{a_0} = \text{peak echo amplitude}$

$$20 \log_{10} \left(\frac{a_1}{2a_0}\right) = \text{echo in dB}$$

$$20 \log_{10} \left(1 + \frac{a_1}{a_0}\right) = 0.5 \text{ dB}$$

$$\frac{a_1}{2a_0} = 10 \frac{\left[\left(\frac{0.5}{20}\right)-1\right]}{2} = 0.0296$$

$$\text{echo} = 20 \log_{10} \left(\frac{a_1}{2a_0}\right) = -30.566 \text{ dB}$$

TEST 2: Distortion is introduced in the second echo pair with an amplitude ripple of 0.5 dB

$$I = 10 \left[\frac{(\sin \Delta x N) - 1}{40} \right]$$

where $\Delta x = \frac{2 \times 360}{215}$ and $0 \leq N \leq 215$

From the test run we get second echo peak value to be -30.53 dB where the calculated value is the same as before -30.566 dB.

TEST 3: Distortion is introduced in the first and second echo pairs with an amplitude ripple of 0.5 dB

$$I = \left(10 \left[\frac{\sin (\Delta x_1 N) - 1}{40}\right] + 10 \left[\frac{\sin (\Delta x_2 N) - 1}{40}\right]\right)/2$$

where $\Delta x_1 = \frac{360}{215}$; $\Delta x_2 = \frac{2 \times 360}{215}$ and $0 \leq N \leq 214$

Because we are summing two sinusoidal amplitude distortions of 0.5 dB each, the resultant distortion needs to be divided by 2 in order for it to be 0.5 dB.

From the test run we get both the first and second echo peak to be -36.2 dB. The calculated first and second echo peak is:

$$20 \log_{10} \left(1 + \frac{a_1}{4a_0} \right)$$

$$\frac{a_1}{4a_0} = \frac{10 \left[\frac{0.5}{20} \right]}{4} = 0.0148$$

$$20 \log_{10} \frac{a_1}{a_0} = 36.58 \text{ dB}$$

Tests 4 through 6 are the same as Tests 1 through 3 respectively, except the peak amplitude distortion is set at 1 dB instead of 0.5 dB (then $K = 2$). Test 7 is the same as Tests 4 or 5 except the distortion is introduced into the eighth echo pair. The results are given in Table 4-1.

TEST 8: Distortion is introduced in the first and eighth echo pairs with an amplitude ripple of 1 dB ($K = 2$)

$$I = (10 \frac{\sin(\Delta X_1 N) - 1}{20} + 10 \frac{\sin(\Delta X_2 N) - 1}{20})/2$$

$$\text{where } \Delta X_1 = \frac{360}{215}; \Delta X_2 = \frac{8 \times 360}{215} \text{ and } 0 \leq N \leq 214$$

CASE II; A sinusoidal phase distortion of various peak-to-peak values. As defined previously the gain and phase are:

$$|G| = 10 \log_{10} \sqrt{I^2 + Q^2}$$

$$\theta = \tan^{-1} \frac{Q}{I}$$

Now we want to have a sinusoidal phase variation, so $\theta = A \sin(\Delta X N)k$. To simplify, let us set $|G| = 0$ dB so that:

TABLE 4-1. TEST RESULTS OBTAINED WITH DEC-20 COMPUTER

| | <u>Peak Ampl. Distortion (dB)</u> | <u>Echo</u> | <u>Simulated* Distortion Peak (dB)</u> | <u>Calculated Distortion Peak (dB)</u> |
|--------|---|-------------|--|--|
| Test 1 | 0.5 | 1 | -30.44 | -30.566 |
| Test 2 | 0.5 | 2 | -30.53 | -30.566 |
| Test 3 | 0.5 | 1 | -36.26 | -36.58 |
| Test 3 | 0.5 | 2 | -36.27 | -36.58 |
| Test 4 | 1 | 1 | -23.76 | -24.29 |
| Test 5 | 1 | 2 | -23.85 | -24.29 |
| Test 6 | 1 | 1 | -29.69 | -30.31 |
| Test 6 | 1 | 2 | -30.04 | -30.31 |
| Test 7 | 1 | 8 | -25.8 | -24.29 |
| Test 8 | 1 | 1 | -29.77 | -30.31 |
| Test 8 | 1 | 8 | -31.82 | -30.31 |

*Actual Distortions outputted by the algorithm are in echo pairs.
The value shown is an average.

$$(1) \log_{10} [I^2 + Q^2]^{1/2} = 0 \text{ and } [I^2 + Q^2]^{1/2} = 1 \text{ or } I^2 + Q^2 = 1$$

$$(2) \frac{Q}{I} = \tan(A \sin(\Delta X N) - k)$$

$$Q = I \tan(A \sin(\Delta X N) - k)$$

Let $A \sin(\Delta X N) - k = \theta$ so that $Q = I \tan \theta$

From (1) we have:

$$I^2 = 1 - Q^2$$

$$\text{From (2)} Q^2 = I^2 \tan^2 \theta = (1 - Q^2) \tan^2 \theta = \tan^2 \theta - Q^2 \tan^2 \theta$$

$$Q^2 + Q^2 \tan^2 \theta = \tan^2 \theta$$

$$Q^2 (1 + \tan^2 \theta) = \tan^2 \theta$$

$$Q = \frac{\tan \theta}{1 + \tan^2 \theta}$$

$$I = \frac{[1 - \tan^2 \theta]}{1 + \tan^2 \theta}^{1/2} = \frac{1}{(1 + \tan^2 \theta)^{1/2}}$$

$$\theta = \tan^{-1} \frac{Q}{I} = \text{phase}$$

To simplify, let us always work in the I-V quadrant so that $Q \leq 0$ and $I \geq 0$, therefore when $\tan \theta \leq 0$, then $|1 + \tan^2 \theta| \geq 0$. In order to fit the RADC format (2's complement) we multiply I and Q by 128.

TEST 1: Sinusoidal phase distortion of 6° peak value is introduced in the first echo pair

$$\theta = 3 \sin(\Delta X N) - k \text{ where } \Delta X = \frac{360}{215}, 0 \leq N \leq 214 \text{ and}$$

$k = \text{offset} \approx 42^\circ$ places θ in fourth quadrant

$$Q = \frac{\tan(3 \sin(\Delta X N) - 42)}{\sqrt{1 + \tan^2(3 \sin(\Delta X N) - 42)}} \text{ and } I = \sqrt{1 - Q^2}$$

From computer simulation we get the first echo to be -31.49 dB.

Analytically we get

$$20 \log_{10} \left(\frac{2\pi x b_1}{4 \times 360} \right) = \text{echo in dB}$$

where b_1 = ripple in degrees

$$b_1 = 6^\circ, 20 \log_{10} \left(\frac{12\pi}{4 \times 360} \right) = -31.64 \text{ dB}$$

TEST 2: Cosinusoidal phase distortion of 6° peak value is introduced in the first echo

$$\theta = 3 \cos(\Delta X N) - 42$$

The computer simulation is basically the same except that for an odd (sin) distortion function the phase angle for the two echoes is 180° apart, whereas for an even (cos) distortion function the two echoes are in phase. The opposite is true for amplitude distortion. That is, for odd function distortions the phase angle for the two echoes is in phase whereas for even distortion function the phase angle for the two echoes is 180° apart.

TEST 3: Sinusoidal phase distortion of 22.92° peak value is introduced in the first echo

$$\theta = 11.46 \sin(\Delta X N) - 42$$

Calculated result is $20 \log_{10} \left(\frac{2\pi x 22.92}{4 \times 360} \right) = -20 \text{ dB}$ and the simulated result is -20.02 dB.

The results for the phase distortion test cases are shown in Table 4-2.

TABLE 4-2. TEST RESULTS OBTAINED WITH DEC-20 COMPUTER

| | <u>Peak Phase Distortion (degrees)</u> | <u>Echo</u> | <u>Simulated Distortion Phase (dB)</u> | <u>Calculated Distortion Phase (dB)</u> |
|--------|--|-------------|--|---|
| Test 1 | 6 | 1 | -31.49 | -31.64 |
| Test 2 | 6 | 1 | -31.49 | -31.64 |
| Test 3 | 22.92 | 1 | -20.02 | -20.0 |

4.5 PROGRAM TEST ON THE HP 2100A

Three tests were run on the algorithm contained in the HP 2100A computer at RADC. The first test is a single echo test involving a peak sinusoidal amplitude distortion of 0.5 dB. The second test is a double echo test involving a peak sinusoidal amplitude distortion of 0.5 dB with one sine wave at twice the frequency of the other. The third test is a single echo test involving a peak phase distortion of six degrees.

To perform the first test, a program has been implemented (now on disk cartridge 45) called "AT10". A listing of this program is given in Appendix 3.

AT10 outputs M sample points of a distorted sine wave given by:

$$I = 10 \frac{[\sin \Delta X N]^{-1}}{40}$$

where: $\Delta X = \frac{360^\circ}{M}$, and $N = 0, 1, 2, \dots, M$

In our case, we have run AT10 with 256 sample points ($M = 255$). As mentioned, the phase component of this test is 0. AT10 produces both the single echo pair and two pair test cases. The

case just described (one echo pair) is printed out in a data file called "AD000"; this file contains 256 octal mode (06 integers, in two records, 128 numbers each; this file is the sequential output of the "I" or amplitude function as N goes from 1 to 256.

To run the double echo-pair, amplitude-distortion-only case, we executed AT10 again but such that AT10 adds to the first waveform, a second one given by

$$I_2 = 10 \frac{\sin(\Delta X_2 N)-1}{40}$$

where: $\Delta X_2 = \frac{2 \times 360}{M}$, and $N = 0, 1, 2, \dots, M = 255$

The superimposed waveform (this is what is printed out into the data file) is

$$I_{\text{sup}} = (I + I_2)/2$$

Again, there are 256 samples, written into two 128-number records in 06 format. The file containing I_{sup} is called "AD001". This double echo-pair that is equivalent to Test 3 of Table 4-1 which shows the theoretical peak distortion to be -36.58 dB.

For the third case, phase distortion only, the program "TEST 1" was executed. The waveform produced by "TEST 1" is a sine whose phase is given by:

$$Q = \frac{\tan(3 \sin(\Delta X_1 N)-42)}{1+\tan^2(3 \sin(\Delta X_1 N)-42)}, \quad X = \frac{360}{256}, \quad N = 0, 1, 2, \dots, 255$$

To run this test case, we executed "TEST 1" (also on disk 45), and used the data file "AD002". This results in a test case of 6^0 phase distortion equivalent to Test 1 in Table 4-2.

Tables 4-3 through 4-5 give printouts of the data contained in the output files for these three test cases, "AD000", "AD001", and "AD002" respectively.

We can now compare the results obtained with the test cases run on the DEC-20 and HP 2100A computers with their respective equalizer algorithms. Slight differences are to be expected because of the differences in precision and the internal mathematical algorithms. Table 4-6 shows the results.

The comparison shows excellent agreement between the two equalizer algorithm outputs (DEC-20 and HP 2100A) and demonstrates that they are performing the way they are supposed to.

TABLE 4-3. OUTPUT TEST 1 (ONE ECHO PAIR)

File AD000

| Tap No. | Attenuator (dB) | (Turns) | Line Stretcher (deg) | (Div) |
|---------|--------------------|---------|-------------------------|-------|
| 8A | -.59754E+02 | 9.924 | .77894E+03 | 7.2 |
| 7A | -.57500E+02 | 9.133 | .84826E+03 | 7.8 |
| 6A | -.50899E+02 | 9.931 | .72472E+03 | 6.7 |
| 5A | -.54626E+02 | 9.280 | .12426E+04 | 11.0 |
| 4A | -.76775E+02 | 9.870 | .13916E+03 | 1.3 |
| 3A | -.57659E+02 | 9.054 | .48888E+03 | 4.5 |
| 2A | -.63654E+02 | 8.213 | .82400E+03 | 7.6 |
| 1A | -.30575E+02 | 2.894 | .94832E+03 | 8.8 |
| 0 | .95424E+01 | 0.000 | .44309E+03 | 4.1 |
| 1B | -.30102E+02 | 2.571 | .40519E+02 | 0.4 |
| 2B | -.58178E+02 | 8.552 | .60589E+03 | 5.6 |
| 3B | -.53561E+02 | 9.354 | .47294E+03 | 4.4 |
| 4B | -.57641E+02 | 9.961 | .80104E+03 | 7.4 |
| 5B | -.52656E+02 | 9.388 | .15492E+03 | 1.4 |
| 6B | -.68077E+02 | 9.716 | .23711E+03 | 2.2 |
| 7B | -.55111E+02 | 9.231 | .61405E+03 | 5.7 |
| 8B | -.58767E+02 | 9.938 | .91032E+03 | 8.4 |

TABLE 4-4. OUTPUT TEST 2 (DOUBLE ECHO PAIR)

File AD001

| Tap No. | Attenuator (dB) | (Turns) | Line Stretcher (deg) | (Div) |
|---------|--------------------|---------|-------------------------|-------|
| 8A | -.58976E+02 | 9.646 | .78231E+03 | 7.2 |
| 7A | -.58854E+02 | 9.603 | .86500E+03 | 8.0 |
| 6A | -.50607E+02 | 9.816 | .85919E+03 | 7.9 |
| 5A | -.55226E+02 | 9.481 | .90270E+03 | 8.4 |
| 4A | -.74326E+02 | 9.505 | .32962E+03 | 3.0 |
| 3A | -.56551E+02 | 8.710 | .36137E+03 | 3.3 |
| 2A | -.36679E+02 | 3.518 | .93857E+02 | 8.7 |
| 1A | -.36044E+02 | 3.898 | .95012E+03 | 8.8 |
| 0 | .95424E+01 | 0.000 | .44309E+03 | 4.1 |
| 1B | -.35637E+02 | 3.589 | .39872E+03 | 3.7 |
| 2B | -.35844E+02 | 2.950 | .49132E+03 | 4.5 |
| 3B | -.52810E+02 | 9.094 | .60045E+03 | 5.6 |
| 4B | -.57316E+02 | 9.856 | .97058E+03 | 9.0 |
| 5B | -.53165E+02 | 9.563 | .13478E+03 | 1.2 |
| 6B | -.66063E+02 | 9.314 | .10264E+03 | 0.9 |
| 7B | -.56190E+02 | 9.654 | .59731E+03 | 5.5 |
| 8B | -.58025E+02 | 9.706 | .90695E+03 | 8.4 |

TABLE 4-5. OUTPUT CASE 3 (PHASE DISTORTION ONLY)

File AD004

| Tap No. | Attenuator (dB) | (Turns) | Line Stretcher (deg) | (Div) |
|---------|--------------------|---------|-------------------------|-------|
| 8A | -.59834E+02 | 9.953 | .79680E+03 | 7.4 |
| 7A | -.59511E+02 | 9.837 | .73877E+03 | 6.8 |
| 6A | -.50643E+02 | 9.831 | .96246E+03 | 8.9 |
| 5A | -.56282E+02 | 9.841 | .11579E+04 | 10.7 |
| 4A | -.72772E+02 | 9.269 | .38686E+03 | 3.6 |
| 3A | -.57695E+02 | 9.066 | .39645E+03 | 3.7 |
| 2A | -.66269E+02 | 8.720 | .67455E+03 | 6.2 |
| 1A | -.31102E+02 | 2.984 | .10384E+04 | 9.6 |
| 0 | .95424E+01 | 0.000 | .44309E+03 | 4.1 |
| 1B | -.31104E+02 | 2.742 | .17235E+03 | 1.6 |
| 2B | -.58022E+02 | 8.500 | .44508E+03 | 4.1 |
| 3B | -.53881E+02 | 9.466 | .78023E+03 | 7.2 |
| 4B | -.57201E+02 | 9.818 | .86518E+03 | 8.0 |
| 5B | -.53831E+02 | 9.794 | .10693E+03 | 1.0 |
| 6B | -.68513E+02 | 9.803 | .20575E+03 | 1.9 |
| 7B | -.56951E+02 | 9.961 | .33624E+03 | 3.1 |
| 8B | -.57922E+02 | 9.674 | .66682E+03 | 6.2 |

TABLE 4-6. COMPARISON OF TEST RESULTS FOR THE DEC-20 AND HP 2100A EQUALIZER ALGORITHMS

| <u>Test</u> | <u>Type of Distortion</u> | <u>Echo Affected</u> | <u>Simulated Echo Level in dB</u> | | <u>Theoretical Level in dB</u> |
|------------------|-------------------------------|----------------------|-----------------------------------|---------------|--------------------------------|
| | | | <u>HP 2100A</u> | <u>DEC-20</u> | |
| Test 1, | 0.5 dB | 1A | -30.58 | -30.44 | -30.57 |
| One Echo Pair | Peak Amplitude Only | 1B | -30.10 | (AVG) | -30.57 |
| Test 2, | | 1A | -36.04 | 36.36 | -36.58 |
| Double Echo Pair | 0.5 dB | 1B | -35.64 | (AVG) | -36.58 |
| | | 2A | -36.68 | | -36.58 |
| | | 2B | -35.84 | | -36.58 |
| Test 3, | 6° Peak Phase Distortion Only | 1A | -31.10 | -31.49 | -31.64 |
| | | 1B | -31.10 | (AVG) | -31.64 |

While this is not 100% conclusive, it does provide a high degree of confidence that the algorithm is working properly. The only real test is the use of the algorithm over many real situations which completely exercise it. Some comments about what to expect are in order.

First of all, the Microwave Transversal Equalizer (MTE) to be used to provide corrections to the distortion has its own inherent second order distortions which are not constant. That is, under one set of amplitude and phase adjustments for each of the taps there is a given "self-distortion" which is included in the data supplied to the algorithm to analyze. When the amplitude and phase settings are now changed to correct for the total distortion reflected in the data, then the new settings of the MTE will correct much of the distortion but because the MTE settings are different from the original settings there will be a new "self-distortion" introduced by the MTE. This means that the correction is imperfect and the process must be iterated until the distortion residue is less than the allowable value (or until the "self-distortion" changes are greater than the corrected indicated by the algorithm).

Another source of distortion lies in the hardware used to provide the data samples. These distortions are:

1. the phase response of the components
2. the amplitude response of the components
3. noise introduced on the data (Gaussian)
4. random spikes (transients induced by interference)

5. sinusoidal variations (coupled interference from motors, oscillators, etc.)
6. timing errors (clocks, circuit switching speeds, etc.)
7. inaccuracies in data samples (improper scaling, etc.)
8. digitizing errors (bit errors in digital operations)

These errors introduce their own "self-distortion" and just as in the MTE limit the residual distortion that can be obtained. In addition, some of the errors are random so that iterations won't help.

Finally, there is the algorithm itself. It cannot be considered fully debugged until all combinations of operation have been exercised. This is not a practical thing to do in the laboratory but instead requires a period of field use. In addition, the algorithm has limits of precision which will ultimately limit the amount of distortion that can be corrected even if the hardware were perfect, although this is the area that is least likely to present a problem.

5. CONCLUSIONS AND RECOMMENDATIONS

Computer algorithms have been successfully developed to provide open-loop adaptive control of the MTE. The algorithms are based upon the application of FFT techniques, and the necessary corollary software programming procedures have been developed and described.

Verification of the aforementioned FFT and associated software programming has also been accomplished at AIL with a DEC-20 computer. Such verification has involved the generation of output adjustment data for MTE control based upon computer analysis of artificially simulated time sidelobe input distortion levels. A similar procedure will be undertaken at RADC using real-time I and Q data acquired at the A. Froelich High Power Tube Facility. Such distortion levels will be processed at RADC using translation of format programs between the AIL DEC-20 and the RADC HP 2100A computers. Preliminary data suggests that the post-delivery program translation will be successful after the normal debugging procedures have been completed.

AIL recommendations for future MTE related efforts include the following:

- Continuation and/or extension of contracted efforts to include AIL post-delivery support for RADC.

- Investigation and definition of suitable closed-loop techniques and procedures for adaptive operation of MTE.
- Development of suitable solid-state time delay devices to replace the present manually adjustable line stretchers.
- Modification of the MTE to expand capability by providing 32 tap operation.
- Development of suitable electronic interface to implement fully adaptive closed-loop operation of the MTE.

APPENDIX 1

**SAMPLE COMPUTER RUN WITH
INPUT DATA**

APPENDIX 1: SAMPLE RUN

This appendix includes a sample run of the program with the input data entitled AD000.

:RU,AIL

1

INITIAL SETTINGS AT STEP 0 SHOULD BE:

ATTENUATOR

1 A=10.000
2 A=10.000
3 A=10.000
4 A=10.000
5 A=10.000
6 A=10.000
7 A=10.000
8 A=10.000
M = 0.000
1 B=10.000
2 B=10.000
3 B=10.000
4 B=10.000
5 B=10.000
6 B=10.000
7 B=10.000
8 B=10.000

} Initial
Attenuator
Settings

LINE STRETCHER

1 A= 7.9
2 A= 6.2
3 A= 3.7
4 A= 1.5
5 A= 9.1
6 A= 7.5
7 A= 7.0
8 A= 6.1
M = 4.1
1 B= 1.2
2 B= 3.7
3 B= 5.2
4 B= 7.2
5 B= .5
6 B= 1.4
7 B= 3.2
8 B= 6.2

} Initial
Line
Stretcher
Settings

APPENDIX 1 SAMPLE RUN (continued)

ENTER THE FILE NAME (Attenuator in dB Units)
AD000

| | | | | | |
|--------------|--------------|--------------|--------------|--------------|--------------|
| - .53372E+02 | - .59486E+02 | - .50322E+02 | - .55781E+02 | - .67727E+02 | - .59106E+02 |
| - .52321E+02 | - .24613E+02 | | | | |
| + .95424E+01 | - .23590E+02 | - .50158E+02 | - .54445E+02 | - .55841E+02 | - .53580E+02 |
| - .64164E+02 | - .56657E+02 | | | | |
| - .57362E+02 | | | | | |
| + .65446E+03 | + .67758E+03 | + .96441E+03 | + .92669E+03 | + .17776E+03 | + .31625E+03 |
| + .84035E+03 | + .94340E+03 | | | | |
| + .44309E+03 | + .40437E+02 | + .58954E+03 | + .64557E+03 | + .76244E+03 | + .11079E+03 |
| + .35742E+03 | + .42473E+03 | | | | |
| + .67480E+03 | | | | | |

APPENDIX 1 SAMPLE RUN (continued)

INTERMEDIATE SETTINGS AT STEP 1 ARE:

ATTENUATOR

1 A= 1.976
2 A= 6.202
3 A= 9.519
4 A= 8.486
5 A= 9.669
6 A= 9.705
7 A= 9.828
8 A= 9.434
M = 0.000
1 B= 1.573
2 B= 6.025
3 B= 9.665
4 B= 9.368
5 B= 9.707
6 B= 8.934
7 B= 9.842
8 B= 9.502

LINE STRETCHER

1 A= 8.8
2 A= 7.8
3 A= 2.9
4 A= 1.6
5 A= 8.6
6 A= 8.9
7 A= 6.3
8 A= 6.1
M = 4.1
1 B= .4
2 B= 5.5
3 B= 6.0
4 B= 7.1
5 B= 1.0
6 B= 3.3
7 B= 3.9
8 B= 6.2

AFTER 0 ITERATIONS DISTORTION CAN NOT BE COMPENSATED

AIL : STOP

Note: XD = 20 in \$AT10 when generating input for this run.

In subsequent runs, XD = 40

APPENDIX 2

**PROGRAM TO GENERATE
TEST DATA**

APPENDIX 2. PROGRAM TO GENERATE TEST DATA

This routine generates ideal sinusoidal distortion as the data file for the program.

```
0001  FTN4.L
0002      PROGRAM AT10
0003      DIMENSION IBUF2(256),IBUF3(256),MBUF(256)
0004      DIMENSION IDC8(272),NAM(3),IBUF0(256),ISIZE(2)
0005      DIMENSION LBUF(256),IBUF1(256)
0006      DIMENSION IDC81(272),NAM1(3)
0007      ITYPE=2
0008      ISIZE=2
0009      ISIZE(2)=128
0010      DATA NAM/2HAD,2H00,2H0/
0011      DATA NAM1/2HAD,2H00,2H1/
0012      CALL CREAT (IDC8,IERR,NAM,ISIZE,ITYPE)
0013      CALL CREAT (IDC81,IERR,NAM1,ISIZE,ITYPE)
0014      N=256
0015      ND=40.
0016      XK1=360.*FLOAT(N-1)
0017      XK2=XK1*2.
0018      DO 30 J=1,N
0019      X=XK1*FLOAT(J-1)
0020      Y=XK2*FLOAT(J-1)
0021      X1=(10.+*(SIN(X*3.1415/180.0)-1))/ND)
0022      X2=(10.+*(SIN(Y*3.1415/180.0)-1))/ND)
0023      LBUF(J)=128*X1
0024      XM=(X1+X2)*2.
0025      MBUF(J)=128*XM
0026      IF (MBUF(J).GE.128) MBUF(J)=127
0027      MBUF(J)=256-MBUF(J)
0028      IF (LBUF(J).EQ.128) LBUF(J)=127
0029      LBUF(J)=256-LBUF(J)
0030  20  CONTINUE
0031      DO 30 I=1,128
0032      IBUF0(I)=LBUF(I)
0033      IBUF2(I)=MBUF(I)
0034  30  CONTINUE
0035      DO 40 K=1,128
0036      IBUF1(K)=LBUF(128+K)
0037      IBUF3(K)=MBUF(128+K)
0038  40  CONTINUE
0039      CALL WRITE(IDC8,IERR,IBUF0)
0040      CALL WRITE(IDC8,IERR,IBUF1)
0041      CALL WRITE(IDC81,IERR,IBUF2)
0042      CALL WRITE(IDC81,IERR,IBUF3)
0043      CALL CLOSE(IDC8,IERR)
0044      CALL CLOSE(IDC81,IERR)
0045      STOP
0046      END
```

This program generates a sinusoid with phase distortion only.

```
LIST,$TEST1:::45
$TEST1 T=00004 IS ON CR00045 USING 00005 BLKS R=0034
AVL3L1 FTM4
0002      PROGRAM TEST1
0003      INTEGER IDC8(272),NAM(3),IBUF0(256),IBUF1(256),LBUF(256)
0004      INTEGER ISIZE(2)
0005      ITYPE=2
0006      N=256
0007      ISIZE=2
0008      ISIZE(2)=128
0009      C      CALL CREAT(IDC8,IERR,NAM,ISIZE,ITYPE)
`010      DATA NAM/ 2HAD,2H00,2H4 /
0011      CALL CREAT(IDC8,IERR,NAM,ISIZE,ITYPE)
0012      DX1=360./FLOAT(N-1)
0013      DO 10 I=1,N
0014      X1=DX1*FLOAT(I-1)
0015      X2=SIN(X1*3.1415/180.)-42.
0016      X3=COS(X1*3.1415/180.)
0017      T=X2/X3
0018      T2=T*T
0019      X4=SORT(1+T2)
0020      IF (T.GT.0) X4=-X4
0021      Q=T/X4
0022      IQ=128.*Q
0023      XI=SORT(1.-Q*Q)
0024      II=128*XI
0025      IF (II.GE.127) II=127
0026      IF (II.LE.-128) II=-128
0027      IF (IQ.GE.127) IQ=127
0028      IF (IQ.LE.-128) IQ=-128
0029      IF (II.LT.0) II=II+256
0030      IF (IQ.LT.0) IQ=IQ+256
0031      LBUF(I)=256*II+IQ
0032      10  CONTINUE
0033      DO 30 J=1,128
0034      IBUF0(J)=LBUF(J)
0035      IBUF1(J)=LBUF(J+128)
0036      30  CONTINUE
0037      CALL WRITE(IDC8,IERR,IBUF0)
0038      CALL WRITE(IDC8,IERR,IBUF1)
0039      CALL CLOSE(IDC8,IERR)
0040      STOP
0041
```

Input for Case 1: 256 samples of sinusoid
listed from sequential
file, in decimal

Input for Case 2:

STOP

Input for Case 1: Octal Format

:LIST,AD000
AD000 T=00002 IS ON CR00002 USING 00002 BLKS R=0128

RECE: 00001

REC# 00002

074000 074000 074000 074000 074000 073400 073400 073400•
073400 073400 073400 073000 073000 073000 073000 073000•
073000 072400 072400 072400 072400 072400 072400 072400•
072000 072000 072000 072000 072000 072000 072000 072000•
071400 071400 071400 071400 071400 071400 071400 071400•
071400 071400 071000 071000 071000 071000 071000 071000•
071000 071000 071000 071000 071000 071000 071000 071000•
071000 071000 071000 071000 071000 071000 071000 071000•
071000 071000 071000 071000 071000 071000 071000 071000•
071000 071000 071000 071000 071000 071000 071000 071000•
071000 071000 071000 071000 071000 071400 071400 071400•
071400 071400 071400 071400 071400 071400 071400 072000•
072000 072000 072000 072000 072000 072000 072000 072400•
072400 072400 072400 072400 072400 072400 073000 073000•
073000 073000 073000 073000 073000 073400 073400 073400•
073400 073400 073400 074000 074000 074000 074000 074000•

Input for Case 2: Octal Format

LIST,AD001

AD001 T=00002 IS ON CR00002 USING 00002 BLKS R=0128

REC# 00001

074000 074400 074400 074400 074400 075000 075000 075000 075000
075000 075400 075400 075400 075400 076000 076000 076000 076000
076000 076000 076400 076400 076400 076400 076400 076400 076400
077000 077000 077000 077000 077000 077000 077000 077000 077000
077000 077000 077400 077400 077400 077400 077400 077400 077400
077400 077400 077400 077400 077400 077400 077400 077400 077400
077400 077400 077400 077400 077400 077400 077400 077400 077400
077400 077400 077400 077400 077400 077400 077400 077400 077400
076400 076400 076400 076400 076400 076000 076000 076000 076000
076000 076000 076000 075400 075400 075400 075400 075400 075400
075000 075000 075000 075000 075000 075000 075000 074400 074400
074400 074400 074400 074400 074400 074000 074000 074000 074000
074000 074000 074000 074000 074000 074000 074000 074000 074000
073400 073400 073400 073400 073400 073400 073400 073400 073400
073400 073400 073400 073400 073400 073400 073400 073400 073400
073400 073400 073400 073400 073400 074000 074000 074000 074000
074000 074000 074000 074000 074000 074000 074000 074000 074000

REC# 00002

074000 074000 074400 074400 074400 074400 074400 074400 074400
074400 074400 074400 074400 074400 074400 074400 075000 075000
075000 075000 075000 075000 075000 075000 075000 075000 075000
075000 075000 075000 075000 075000 075000 075000 075000 075000
074400 074400 074400 074400 074400 074400 074400 074400 074400
074400 074400 074400 074400 074400 074000 074000 074000 074000
074000 073400 073400 073400 073400 073400 073400 073400 073400
073000 073000 073000 073000 073000 072400 072400 072400 072400
072400 072400 072400 072000 072000 072000 072000 072000 072000
072000 071400 071400 071400 071400 071400 071400 071400 071400
071400 071400 071400 071400 071400 071000 071000 071000 071000
071000 071000 071000 071000 071000 071000 071000 071000 071000
071400 071400 071400 071400 071400 071400 071400 071400 071400
071400 072000 072000 072000 072000 072000 072000 072000 072000
072400 072400 072400 072400 072400 073000 073000 073000 073000
073400 073400 073400 073400 073400 074000 074000 074000 074000

Input for Case 3: Octal Format

LIST,AD004

AD004 T=00002 IS ON CR00002 USING 00002 BLKS R=0128

REC# 00001

057653 057653 057653 057653 057653 057653 057654 057654•
057654 060254 060254 060254 060254 060254 060255 060255•
060255 060255 060655 060655 060655 060655 060655 060656•
060656 060656 060656 060656 060656 061256 061256 061256•
061256 061257 061257 061257 061257 061257 061257 061257•
061257 061257 061257 061257 061657 061657 061657 061660•
061660 061660 061660 061660 061660 061660 061660 061660•
061660 061660 061660 061660 061660 061660 061660 061660•
061660 061660 061660 061660 061660 061660 061660 061660•
061660 061660 061660 061660 061660 061660 061660 061660•
061660 061660 061660 061660 061660 061660 061660 061660•
061660 061657 061657 061257 061257 061257 061257 061257•
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OP_CODE_ERR 057654 057654 057653 057653 057653 057653 057653•

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057653 057253 057253 057252 057252 057252 057252 057252•
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Input for Case 3:
Decimal Format

| | | | | | | | | |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 24491 | 24491 | 24491 | 24491 | 24491 | 24491 | 24491 | 24492 | 24492 |
| 24492 | 24748 | 24748 | 24748 | 24748 | 24748 | 24749 | 24749 | 24749 |
| 24749 | 24749 | 25005 | 25005 | 25005 | 25005 | 25005 | 25005 | 25005 |
| 25006 | 25006 | 25006 | 25006 | 25006 | 25006 | 25006 | 25006 | 25006 |
| 25262 | 25263 | 25263 | 25263 | 25263 | 25263 | 25263 | 25263 | 25263 |
| 25263 | 25263 | 25263 | 25263 | 25263 | 25263 | 25263 | 25263 | 25263 |
| 25520 | 25520 | 25520 | 25520 | 25520 | 25520 | 25520 | 25520 | 25520 |
| 25520 | 25520 | 25520 | 25520 | 25520 | 25520 | 25520 | 25520 | 25520 |
| 25520 | 25520 | 25520 | 25520 | 25520 | 25520 | 25520 | 25520 | 25520 |
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| 25520 | 25519 | 25519 | 25519 | 25519 | 25519 | 25519 | 25519 | 25519 |
| 25263 | 25263 | 25263 | 25263 | 25263 | 25263 | 25263 | 25263 | 25263 |
| 25262 | 25262 | 25262 | 25262 | 25262 | 25262 | 25262 | 25262 | 25262 |
| 25006 | 25006 | 25005 | 25005 | 25005 | 25005 | 25005 | 24749 | 24749 |
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| 24492 | 24492 | 24491 | 24491 | 24491 | 24491 | 24491 | 24491 | 24491 |
| 24491 | 24235 | 24235 | 24234 | 24234 | 24234 | 24234 | 24234 | 24234 |
| 24234 | 24234 | 23978 | 23977 | 23977 | 23977 | 23977 | 23977 | 23977 |
| 23977 | 23977 | 23977 | 23977 | 23720 | 23720 | 23720 | 23720 | 23720 |
| 23720 | 23720 | 23720 | 23720 | 23720 | 23720 | 23720 | 23463 | 23463 |
| 23463 | 23463 | 23463 | 23463 | 23463 | 23463 | 23463 | 23463 | 23463 |
| 23463 | 23463 | 23463 | 23463 | 23463 | 23463 | 23463 | 23463 | 23463 |
| 23206 | 23206 | 23206 | 23206 | 23206 | 23206 | 23206 | 23206 | 23206 |
| 23206 | 23206 | 23206 | 23206 | 23206 | 23206 | 23206 | 23206 | 23206 |
| 23206 | 23206 | 23206 | 23206 | 23206 | 23206 | 23206 | 23206 | 23206 |
| 23206 | 23206 | 23206 | 23206 | 23206 | 23206 | 23206 | 23206 | 23206 |
| 23206 | 23206 | 23462 | 23463 | 23463 | 23463 | 23463 | 23463 | 23463 |
| 23463 | 23463 | 23463 | 23463 | 23463 | 23463 | 23463 | 23463 | 23463 |
| 23463 | 23720 | 23720 | 23720 | 23720 | 23720 | 23720 | 23720 | 23720 |
| 23720 | 23720 | 23720 | 23721 | 23977 | 23977 | 23977 | 23977 | 23977 |
| 23977 | 23977 | 23977 | 23977 | 23978 | 24234 | 24234 | 24234 | 24234 |
| 24234 | 24234 | 24234 | 24234 | 24234 | 24235 | 24491 | 24491 | STOP |

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